PRECISION GPS EPHEMERIDES
AND BASELINES

Final Report for NASA Grant No. NAGW-2717
January 1991 - June 1992

CENTER FOR SPACE RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN   AUSTIN, TEXAS

PRECISION GPS EPHEMERIDES AND BASELINES
NASA GRANT NO. NAGW-2717

Final Report
January 1, 1991 – June 30, 1992

INTRODUCTION

The emphasis of this grant was focused on precision ephemerides for the Global Positioning System (GPS) satellites for geodynamics applications. During the period of this grant, major activities were in the areas of thermal force modeling, numerical integration accuracy improvement for eclipsing satellites, analysis of GIG '91 campaign data and the Southwest Pacific campaign data analysis.

THERMAL FORCE AND ECLIPSING ORBITS

Papers on thermal imbalance force modeling and eclipsing orbit analysis were presented at the AIAA Space Flight Mechanics Conference held in February 1992 at Houston, Texas. Details are included in Appendix VII and Appendix VIII of the Final Report for NASA Grant No. NAG5-940.

GIG '91 DATA ANALYSIS

An intensive global GPS observation campaign called "The First GPS IERS and Geodynamics Experiment – GIG '91" was organized by the Jet Propulsion Laboratory for a period of three weeks during early 1992. The campaign spanned part of GPS Weeks 576, 577, 578 and part of Week 579 starting from January 22, 1992, to February 13, 1992. About 120 stations distributed globally, collected data during this period using a variety of GPS receivers which included Rogues, TI-4100's, Trimbles, Ashtechs, Mini Mac 2816 AT's, WM-102's; in addition, data from the five continuously operating DMA stations were also available. From among these, data from 20 globally distributed stations were chosen for orbit determination and Earth orientation parameter determination experiments at UT/CSR. Of these, 17 sites had Rogue receivers, two TI-4100 and one Mini Mac

2816AT. Orbit determination experiments included computation of orbits using data from a reduced set of global stations and from an expanded set, and comparing the baselines and other criteria to assess the orbit accuracy. In addition to the GIG'91 data set mentioned above, data collected during the 1989 South West Pacific Campaign also were used. Results of this study were presented at the 1991 AGU Spring Meeting held at Baltimore, Maryland, during May 1991. Further details are included in the Appendix.

Using the same GIG'91 data set several experiments were performed at CSR to determine the pole positions (X_p, Y_p) during this time period. The main objective of the experiments was to explore strategies for determining the Earth orientation parameters (EOP), polar motion and UT1, using global GPS data. Short arc and long arc with sub arc parameters were considered as possible approaches. The estimated pole positions were compared with SLR and VLBI determined polar motion series in order to assess the quality of these determinations. Results of this study were presented in the special workshop held in Ahrweiler, Germany, during August 1991 and at the XX General Assembly of the IUGG during August 1991 in Vienna, Austria. A copy of the presentation is included in the Appendix.

SWP CAMPAIGN DATA ANALYSIS

Analysis of data collected during the South West Pacific (SWP) campaigns contributed to accuracy assessment of the GPS satellite orbits. The SWP campaign data were collected during the summers of 1988, 1989 and 1990 and these data have been analyzed in various stages at CSR. These data sets complement the CIGNET data in forming a better global distribution and facilitates various orbit and baseline experiments. Studying the repeatability of baselines between various sites in the SWP network provides one method to evaluate the accuracy level of the computed orbits. In depth analysis of few weeks of data collected at the sites in Tonga region (SWP) during the above three years were performed at CSR and the results indicate that the computed GPS orbits yield baseline

repeatability at the 10 to 20 parts per billion (ppb) level. A brief summary of these results were presented at the 1991 AGU Fall Meeting held in San Francisco during December 1991. Copy of the presentation is included in Appendix.

CONCLUSION

Based on the research efforts at CSR in the area of precise ephemerides for GPS satellites, the following observations can be made pertaining to the status and future work needed regarding orbit accuracy. There are several aspects which need to be addressed in discussing determination of precise orbits, such as force models, kinematic models, measurement models, data reduction/estimation methods etc. Although each one of these aspects has been studied at CSR in research efforts under this (and the previous) grant, only points pertaining to the force modeling aspect are addressed here.

Dynamic Modeling – Current Status

At present the following known forces are modeled in routine computation of GPS satellite orbits:

(1) Nonspherical Earth gravity acceleration represented by one of the extant gravity fields such as GEM-L2, GEM-T1 or GEM-T2 truncated to 8×8 is adequate. However, increasing the degree and order and/or tuning the field (at least the resonance coefficients) for GPS orbits may slightly improve the accuracy of this perturbation modeling.

(2) represented as point masses are adequate.

(3) force modeling and the geometric tide effects must be considered in the measurement models.

(4) Perturbation due to solar radiation pressure is adequately modeled by the ROCK4 models; however, it is necessary to scale these accelerations by at least one adjustable parameter.

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(5) Perturbation due to venting of the heat source in the GPS satellite is modeled as 'Y-bias acceleration' scaled by an adjustable parameter.

Values of weekly estimates of this scale parameter considered over a period of time do not exhibit any systematic trend except for a somewhat weak correlation with the eclipsing period. Experience shows that it is necessary to include this perturbation along with an adjustable parameter in order to obtain good fit of the data. However, in a long arc solution, considering several sub arcs for this perturbation does not significantly improve the rms of fit.

Following are some of the factors which could contribute to additional improvement of orbit accuracy beyond the current level.

(1) Perturbation due to imbalance in thermal radiation has been shown to cause differences in orbit prediction at the level of a few meters over a period of about one week or more. Although small, inclusion of this perturbation may help in achieving baseline accuracies (and/or repeatabilities) at parts per billion level. But the difficulty in considering this perturbation routinely is due to the fact that nonlinear partial differential equations (heat equations) must be solved simultaneously with the ordinary differential equations of motion, which causes significant complications in algorithm and computation even for a modest approximation of the satellite configuration. Hence, careful evaluation of the costs and benefits of including this perturbation is needed.

(2) handling discontinuities in function values (occurring in SRP acceleration at shadow crossings), can be overcome by the ad hoc modification of the integrator back difference table. However, inclusion of this modification did not seem to improve the rms of fit or the prediction error in real data processing, although improvements were obvious in simulation studies. The reason for this anomaly is not known at present and will have to be investigated before this feature can routinely be included in orbit computation.

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Dynamic Modeling – Future Study

There are indications (evidenced by discontinuities in daily/weekly solutions and by prediction errors) to the effect that all the perturbations described above do not completely or exactly represent all the forces acting on the GPS satellites. There may be other unmodeled forces such as unintentional thrusting (due to outgassing, momentum dumping, attitude correction etc.) or due to other natural phenomena. One of the ways in which such unknown and unmodeled perturbations could be accounted for in orbit computation is to estimate empirical accelerations. Such an approach needs detailed analysis in the future.

APPENDIX

1. "GPS Ephemeris Accuracy Improvement From Global Data Set," AGU 1991 Spring Meeting, May 28–31, 1991, Baltimore, Maryland.

2. "Analysis of GIG 91," presented at GIG Workshop, Ahrweiler, Germany, August 1991.

3. "Global GPS Orbit Determination," XX General Assembly, IUGG, August 11–24, 1991, Vienna, Austria.

4. "Geodetic Analysis of GPS Measurements Near the Tonga Trench: 1988–1990," AGU 1991 Fall Meeting, December 1991, San Francisco, California.

5. "GPS Reference Frames and Earth Rotation," *Proc. Sixth International Geodetic Symp. on Satellite Positioning,*, Columbus, Ohio, March 17–20, 1992.

6. "GPS Orbit Accuracy," *Proc. Sixth International Geodetic Symp. on Satellite Positioning,*, Columbus, Ohio, March 17–20, 1992.

7. "GPS Reference Frames and Orbit Accuracy," AGU Spring Meeting, Montreal, Canada, May 12–16, 1992.

GPS EPHEMERIS ACCURACY IMPROVEMENT FROM GLOBAL DATA SET

P.ABUSALI, B.SCHUTZ, B.TAPLEY, D.KUANG
CENTER FOR SPACE RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

AGU 1991 SPRING MEETING
MAY 28 - 31, 1991
BALTIMORE, MARYLAND
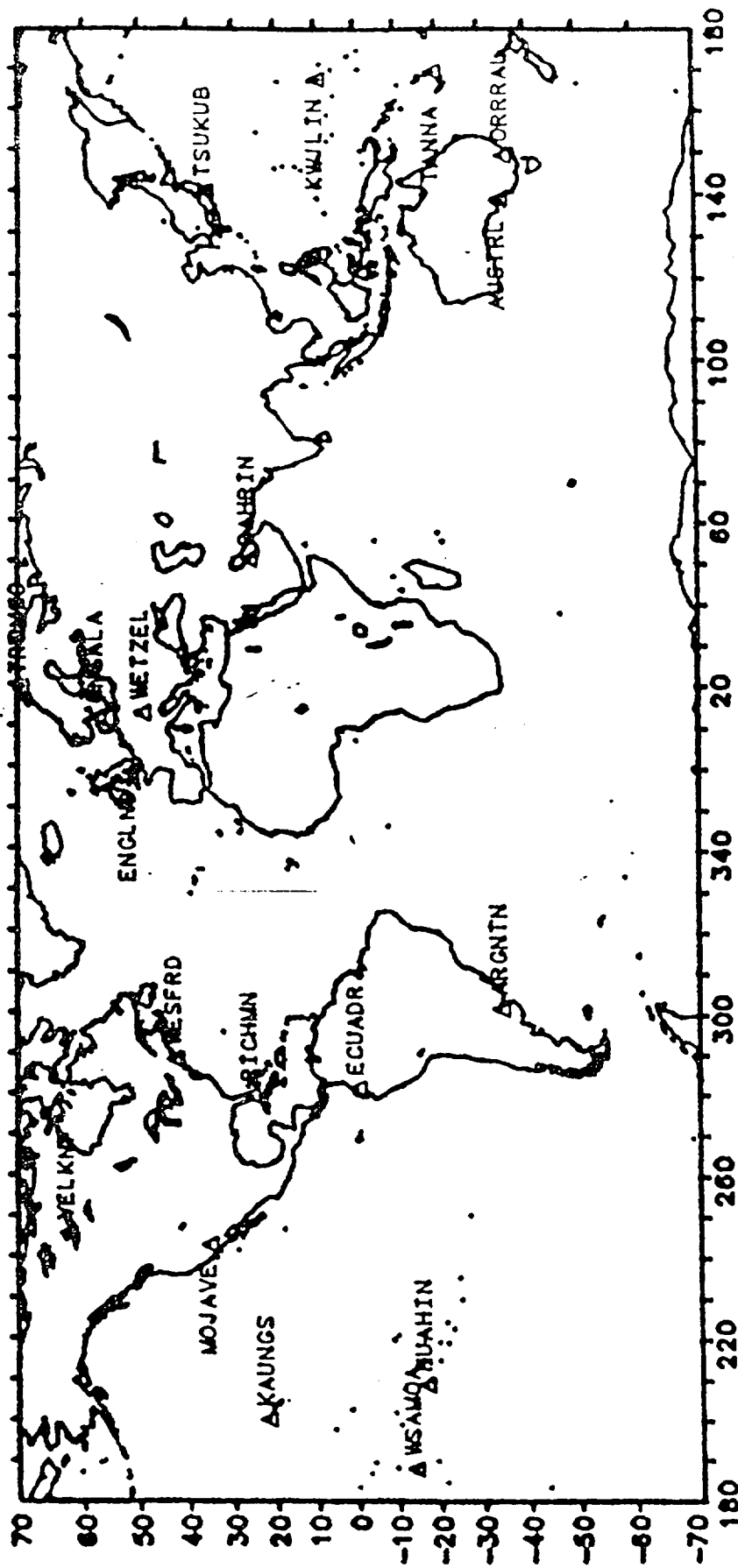
LOCATIONS OF STATIONS WHICH OBSERVED DURING S.W.PACIFIC CAMPAIGN
INCLUDING THE FIVE DMA STATIONS (TOTAL 19) ; GPS WEEK-499

GLOBAL TRACKING NETWORK DATA FOR WEEK 499

CIGNET	AUGMENTED	DMA
Mojave, CA (MM)	Orroral, Australia (TI)	Buenos Aires, Argentina (TI)
Westford, MA (MM)	Huahine, Fr.Polynasia (TI)	Quito, Ecuador (TI)
Yellowknife, NWT (TI)	Tanna (TI)	Smithfield, Australia (TI)
Kauai, HI (TI)	Western Samoa (TI)	Hermitage, England (TI)
Wettzell, Germany (MM)	Kwajalein (TI)	Bahrain (TI)
Onsala, Sweden (TI)	Santo (TI)	
Tromso Norway (TI)		
Tsukuba, Japan (MM)		
Richmond, FL (MM)		

SOLUTION CHARACTERISTICS FOR THE GLOBAL DATA SET

	WEEK 499	WEEK 500
NO. OF STATIONS	9	9
NO. OF DD OBSERVATIONS	43294	38189
NO. OF ESTIMATED PARAMETERS	436	373
RMS OF FIT (CM)	2.54	2.66

	WEEK 499	WEEK 500
NO. OF STATIONS	20	19
NO. OF DD OBSERVATIONS	106417	94916
NO. OF ESTIMATED PARAMETERS	1016	906
RMS OF FIT (CM)	2.904	2.877

TROMSO-ONSALA VECTOR BASELINE ACCURACY
COMPARISON WITH VLBI SOLUTION

	Week 499			Week 500	
	10 GS	20 GS	10 GS	19 GS
North (M)	-0.0286	-0.0313	-0.0591	0.0479
East (M)	-0.0112	-0.0670	-0.0194	0.0229
Vertical (M)	0.0757	0.0127	0.0668	0.0312
Length (M)	-0.022	-0.048	-0.054	-0.042
	(1.5×10^{-8})	(3.4×10^{-8})	(3.8×10^{-8})	(3.0×10^{-8})

RMS OF TRAJECTORY DIFFERENCES
9 GS vs 20 GS SOLUTIONS

PRN	RADIAL (M)		A-TRACK (M)		C-TRACK (M)	
	9 GS	20 GS	9 GS	20 GS	9 GS	20 GS
3	2.043	1.836	15.571	5.736	6.244	1.571
6	3.011	2.463	60.891	68.912	22.859	26.330
9	2.204	1.931	5.920	8.556	2.017	3.222
11	0.728	1.044	5.104	2.443	1.927	1.094
12	2.312	1.403	30.271	20.761	10.978	8.258
13	2.015	1.657	10.176	15.882	3.923	6.074

(Pred vs Fit) in W500 for PRN-03
9 Ground Stations

Radial
A-Track
C-Track

Components : R, A, C (M)

Time (Day)
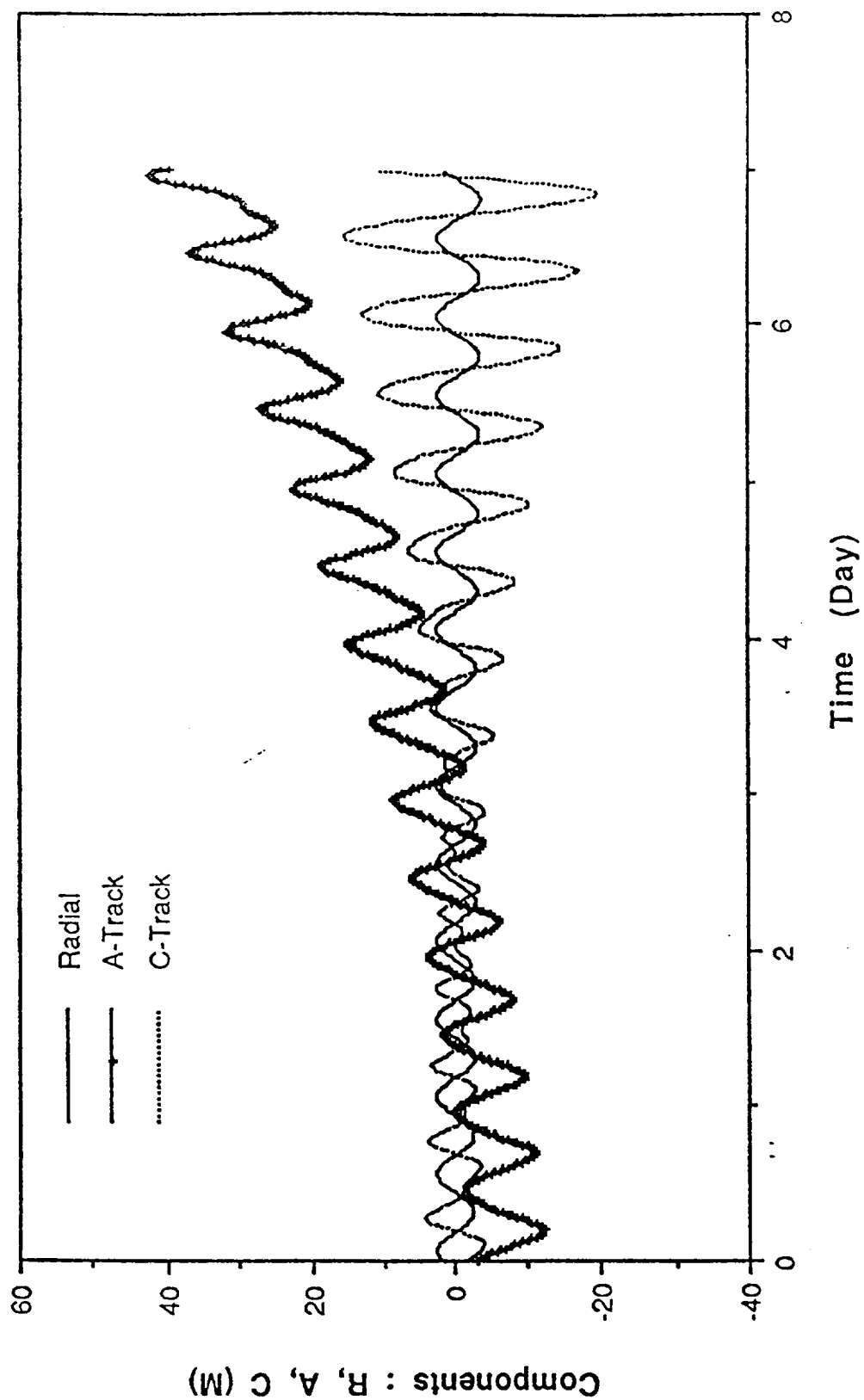
(Pred vs Fit) in W500 for PRN-03
20 Ground Stations

Components : R, A, C (M)

Time (Day)

Radial
A-Track
C-Track
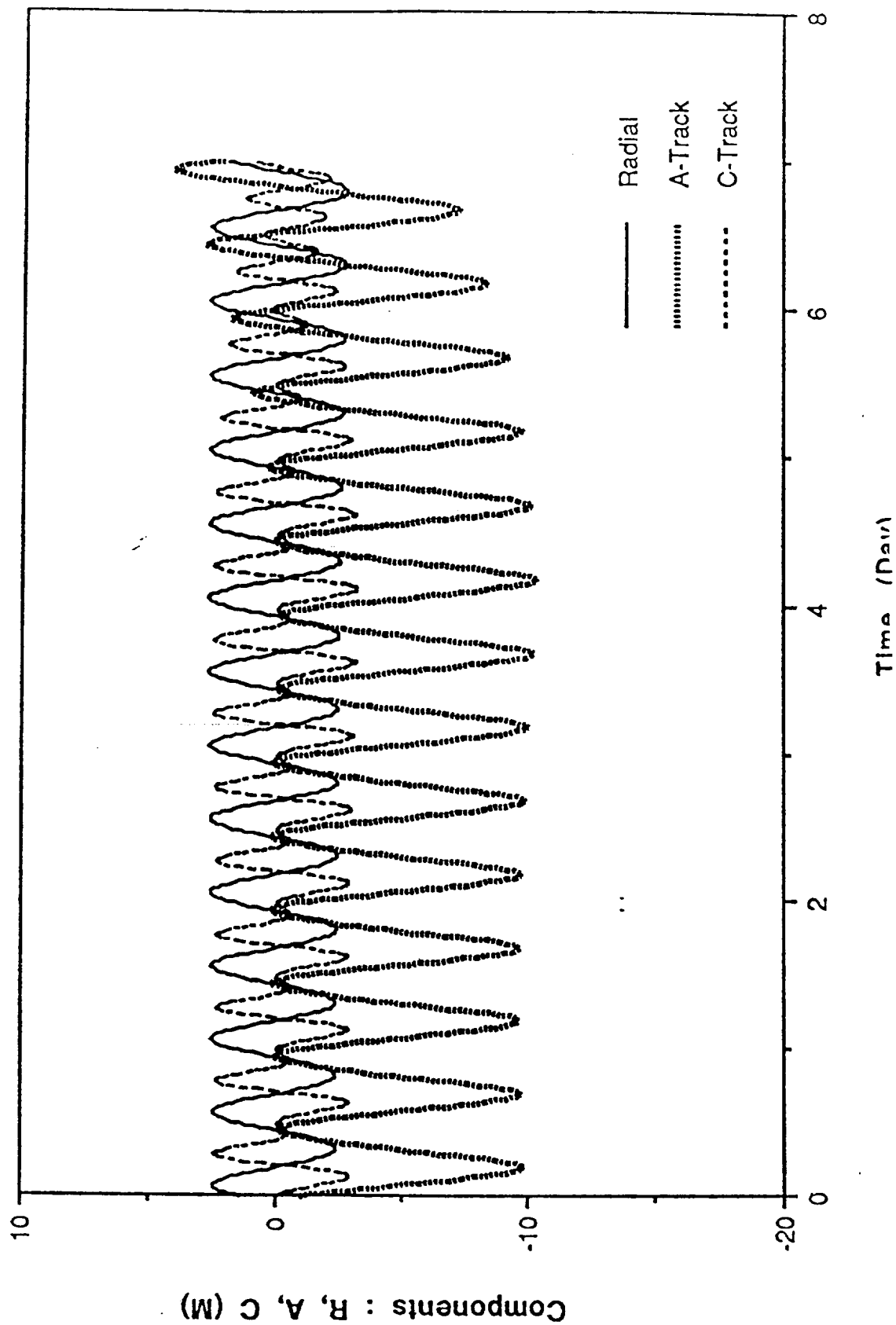
(Pred vs Fit) in W500 for PRN-09
9 Ground Stations

Time (Day)

Components : R, A, C (M)

Radial
A-Track
C-Track
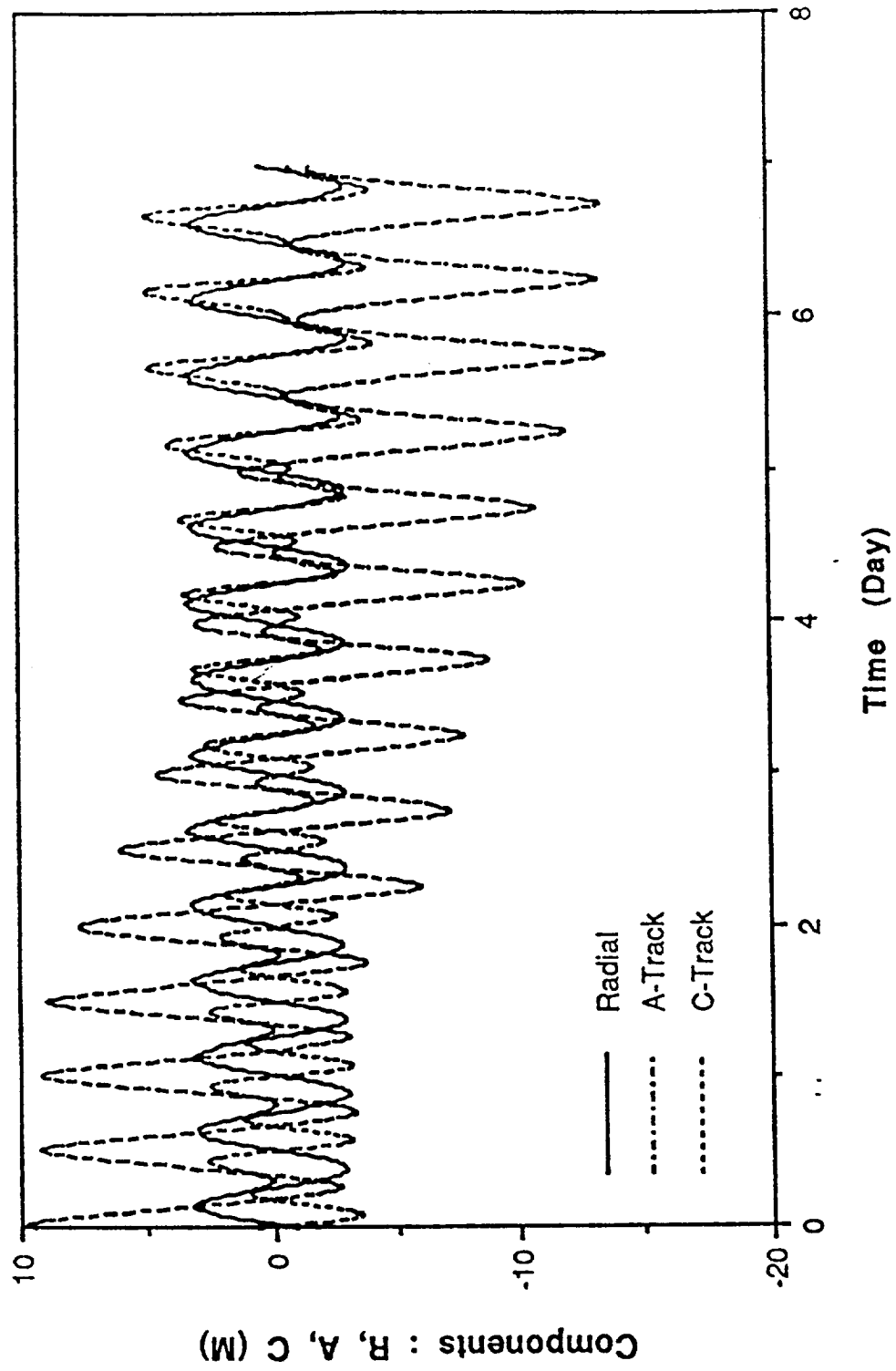
(Pred vs Fit) in W500 for PRN-09
20 Ground Stations

Time (Day)

Components : R, A, T (M)

Radial
A-Track
C-Track
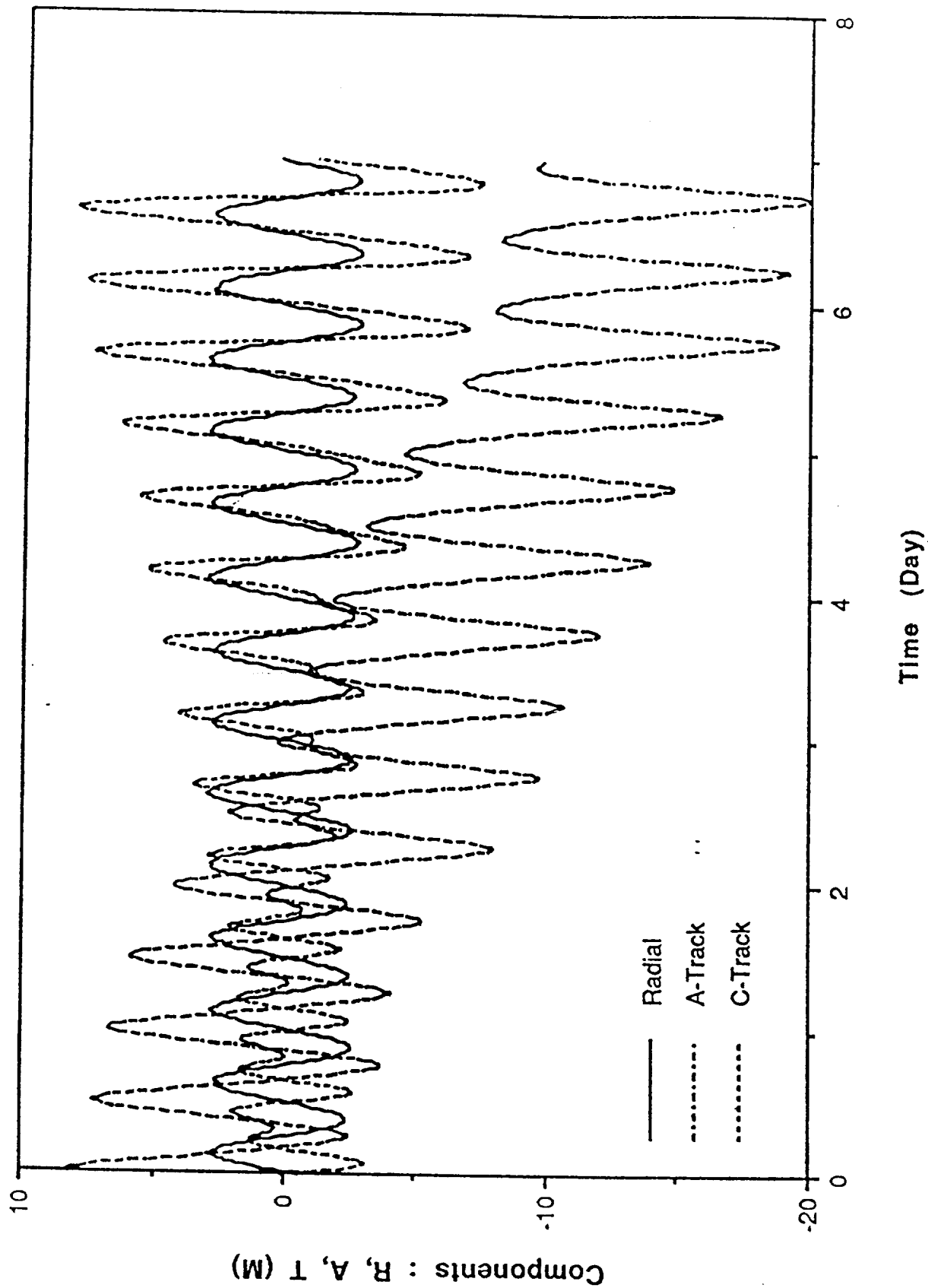
ECF EPH DIFFERENCES (WEEK 499)

(UT/CSR DD PHASE SOLN - NSWC EPH)

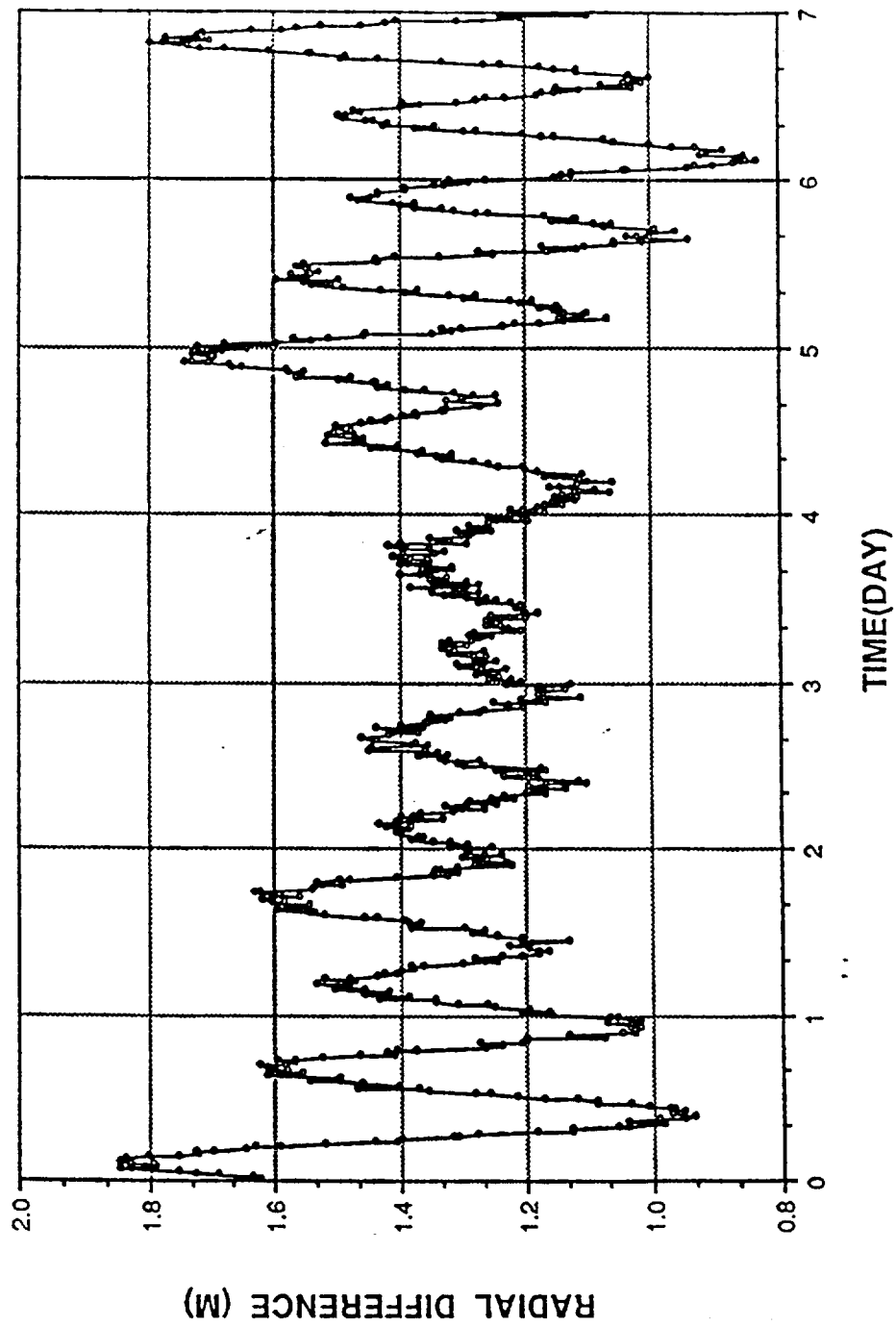|	3	6	9	11	12	13
			MEAN(m)			
Radial	-1.335	-1.348	-1.343	-1.316	-1.264	-1.313
A-Track	-1.898	-0.272	-0.801	1.037	-2.153	0.451
C-Track	0.482	0.487	0.452	0.049	-0.143	-0.158
			RMS(m)			
Radial	1.618	1.571	1.721	1.421	1.317	1.405
A-Track	3.133	2.228	2.442	1.752	2.777	1.475
C-Track	4.633	4.187	3.568	2.489	3.795	2.376

ECFEPH DIF(CSR—NSWC) SV PRN— 3
W499:CSR DD SOLN (15+3)GS:GLB499S.EST
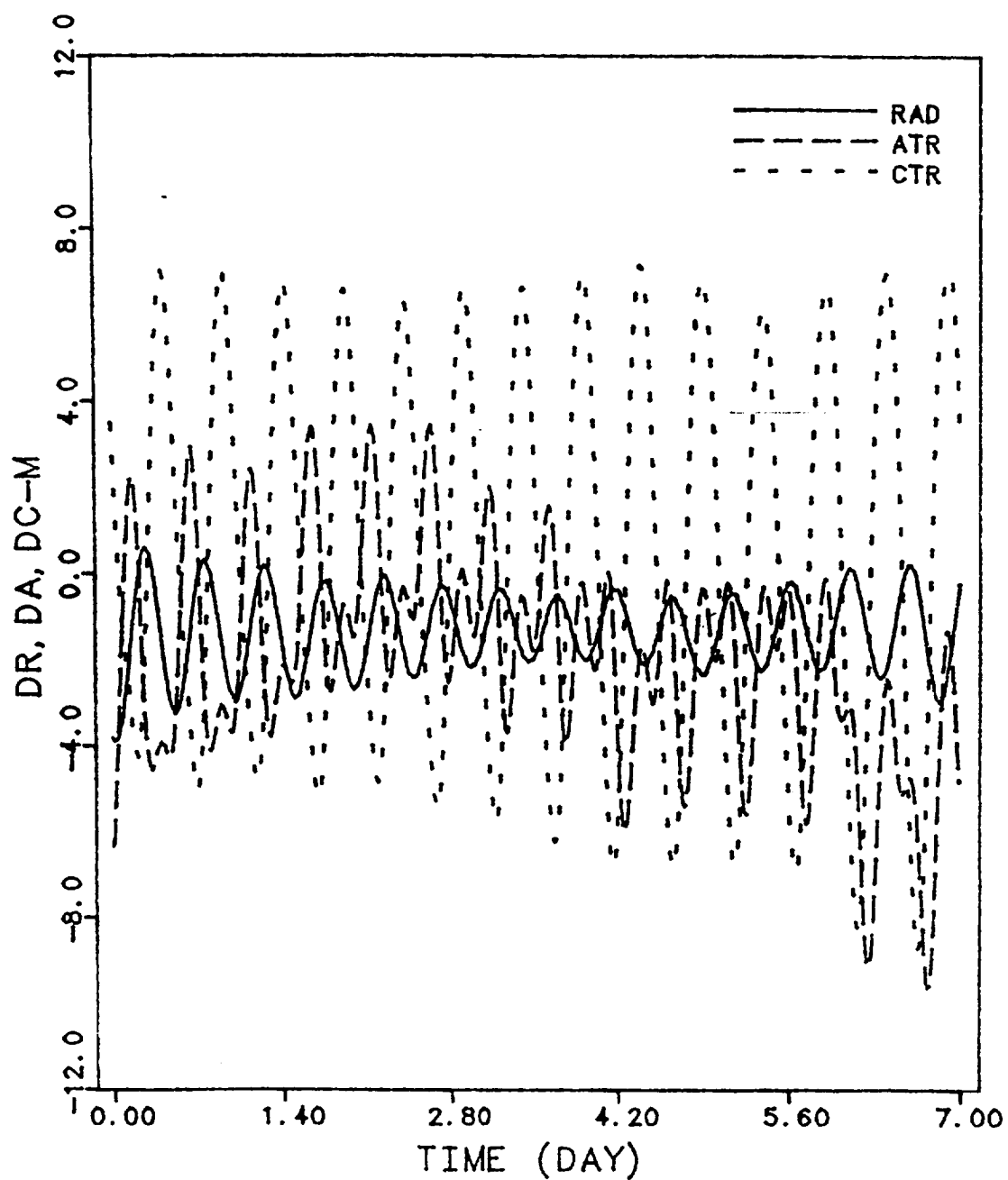
ECFEPH DIF(CSR−NSWC) SV PRN− 9
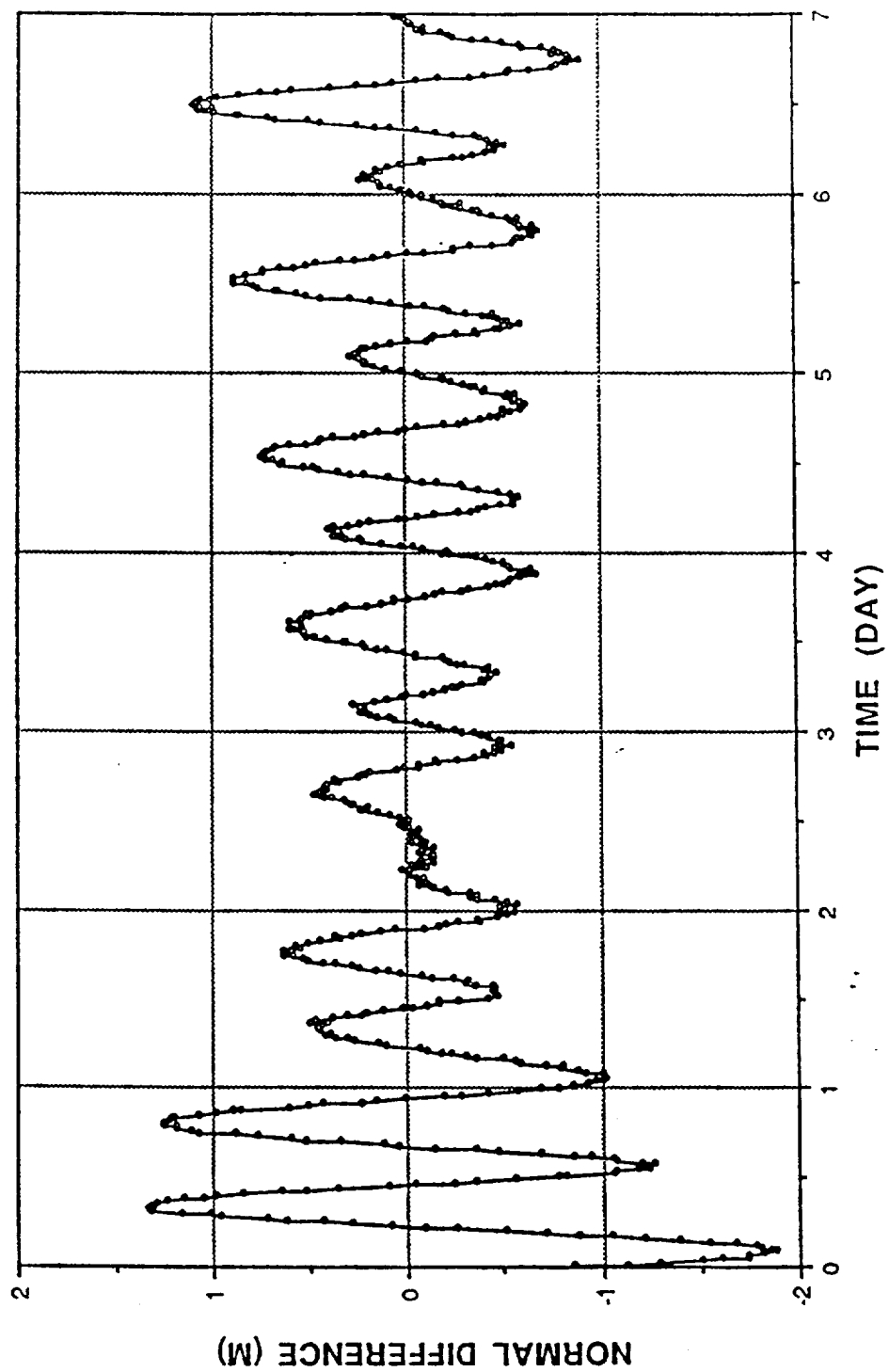W499:CSR DD SOLN (15+3)GS:GLB499S.EST
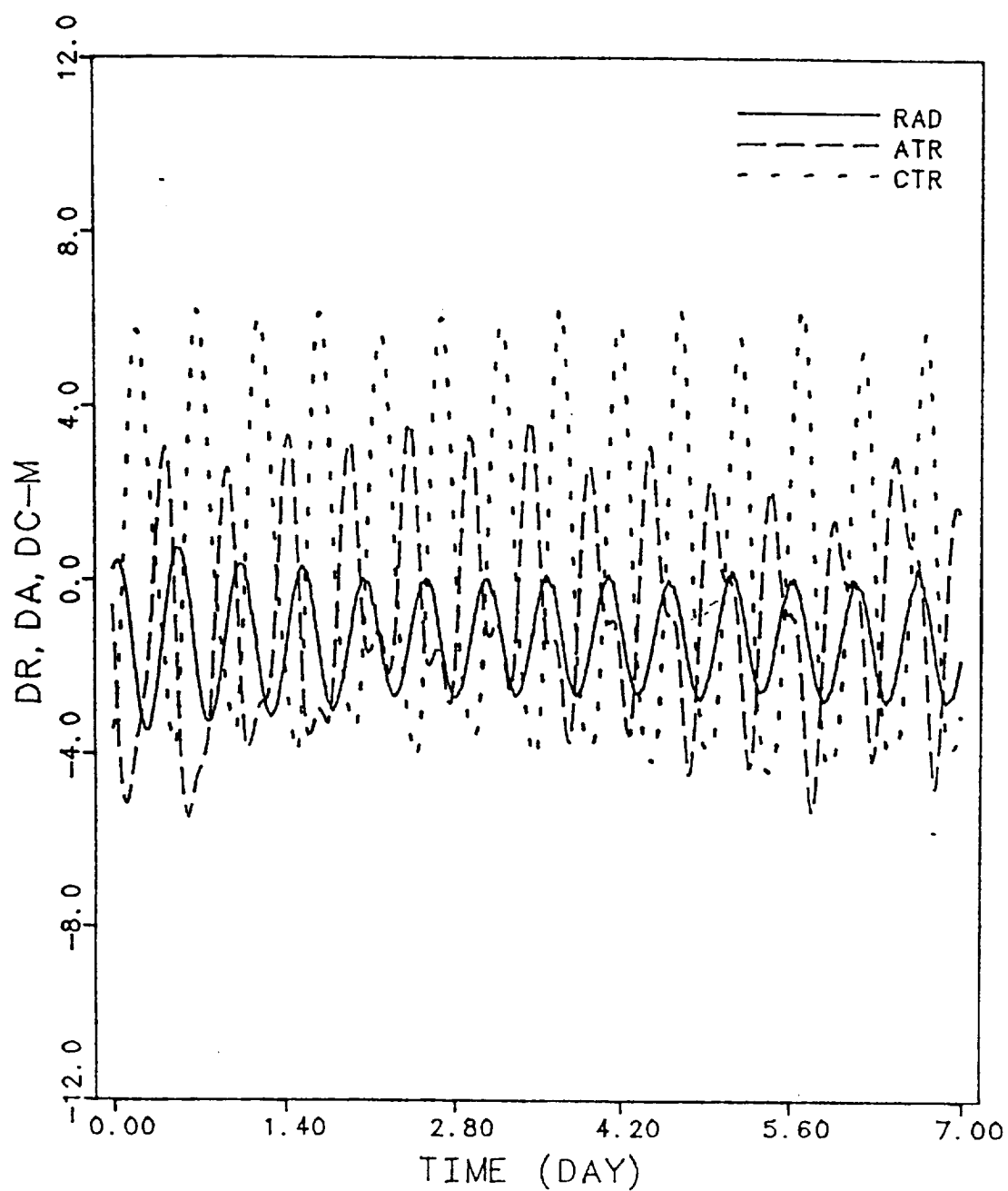
RAD
ATR
CTR

DR, DA, DC−M

TIME (DAY)

NSWC/UTCSR TRAJECTORY FIT (FOR SV#3, WK499)

NSWC/UTCSR TRAJECTORY FIT (FOR SV#3,WK499)

NSWC/UTCSR TRAJECTORY FIT (FOR SV#3,WK499)

TIME (DAY)

NORMAL DIFFERENCE (M)
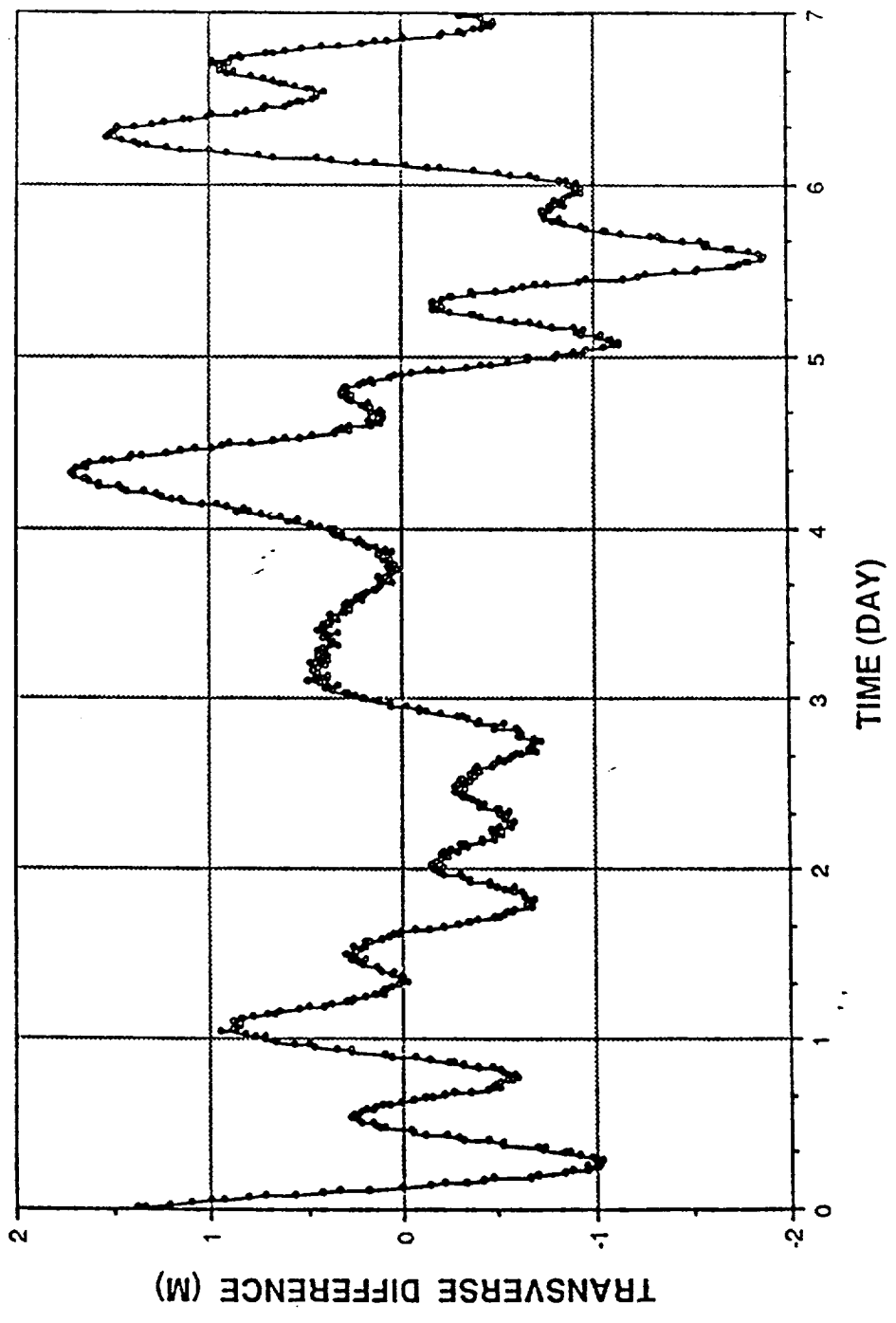
Agenda

Monday, 5 August 1991

Arrival of the participants

19.00 - 20.00   Open-air reception by good weather otherwise in the restau-
rant of the hotel

Tuesday, 6 August 1991

08.00 - 09.00   Registration

09.00 - 10.30   **Opening Session** (Chair: H. Seeger, IFAG)

Greeting and Remarks from Hosts: H. Seeger (IFAG)

Greeting and Remarks from IERS-Background and objectives of
the IERS GPS Campaign: M. Feissel? (IGN)

Greeting and Remarks from the IERS GPS Technique
Coordinator: W. Melbourne (JPL)

IERS Latest UTPM Results for the GIG Experiment Period:
M. Feissel? (IGN)

10.30 - 11.00   Coffee break

11.00 - 12.30   **The Field Campaign** (Ch: W. Schlüter, IFAG/R. Neilan, JPL)

Summary of the Campaign-Planning, Standards, Procedures,
Operations, Performance, etc: R. Neilan/S. Fisher (JPL)

Reports from Various Operations Teams (Representatives from
organizations that participated in field ops will be asked to
give a brief account of their experiences, insights, etc.)

12.30 - 14.00   Lunch

14.00 - 15.30   **The Field Campaign (cont.)**

Continued Reports from Ops Teams

Discussion: Lessons Learned, Recommendations for Future
Campaigns (Standards, Procedures, Documentation, etc.)

15.30 - 16.00   Coffee break

16.00 - 18.00   **Data Analysis - I: Preparation**

Status of Data Pre-Processing & Distrib., Site Ties
(S. Fisher)
Reports by Pre-Processing Centers (All)
Summary of Analysis Standards Proposed by JPL (G. Blewitt)
Discussion of above and related topics

19.00   Open-air grillparty

08.30 – 10.30   Data Analysis – II: Results – The plan is to organize this all-day session by
                 topics. Those with results in several areas will therefore give several short
                 presentations. The main topics are:

                 1. Descriptions of software and modeling strategies
                 2. Baseline Solutions
                 3. GPS Orbit Solutions
                 4. Earth Orientation Solutions
                 5. Geocenter Solutions
                 6. Discussion, Comparison & Analysis of Results

                 As of 25 July, the known groups planning to present results are:
                 U. Texas – B. Schutz
                 DGFI – K. Kaniuth
                 NSWC – E. Swift
                 UNAVCO – C. Rocken
                 MIT – R. King
                 JPL – Blewitt, Lichten, Lindqwister, Webb, Yunck
                 There is still space for more

10.30 – 11.00   Coffee break

11.00 – 12.30   Data Analysis – II: Results (cont.)
                 (See Above)

12.30 – 14.00   Lunch

14.00 – 15.30   Data Analysis – II: Results (cont.)
                 (See Above)

15.30 – 16.00   Coffee break

16.00 – 18.00   Data Analysis – II: Results (cont.)
                 (See Above)

19.30   Bus departure for wine-tasting

20.00 – 22.30   Wine-tasting in Ahrweiler

22.30   Busses return to hotel

Thursday, 8 August 1991

08.30 – 10.00   Special Topics (Preliminary list):

                 Multipath studies with GIG data (C. Rocken)
                 Do high latitude sites pose special problems? (TBD)
                 Implications of SA/AS for global GPS measurements (T. Yunck)
                 Status of SCAR GPS geodesy project in Antarctica (J. Manning)
                 Summary of early GIG results (TBD)

10.00 – 10.30   Coffee break

10.30 – 12.30   Open Discussion (Suggested topics):

                 Implications of early GIG results
                 Establishing a GPS-based global reference frame Integrating GPS into IERS
                 operations and products Plans for a follow-up GIG'91 workshop before IGS
                 campaign?

12.30   Lunch

14.30   Sightseeing tour through the Ahr Valley

ANALYSIS OF GIG 91

B. Schutz, P. Abusali, M. Watkins,
H. Rim, and B. Tapley

Center for Space Research
The University of Texas at Austin

GIG Workshop
Ahrweiler, Germany
August 1991

SUMMARY
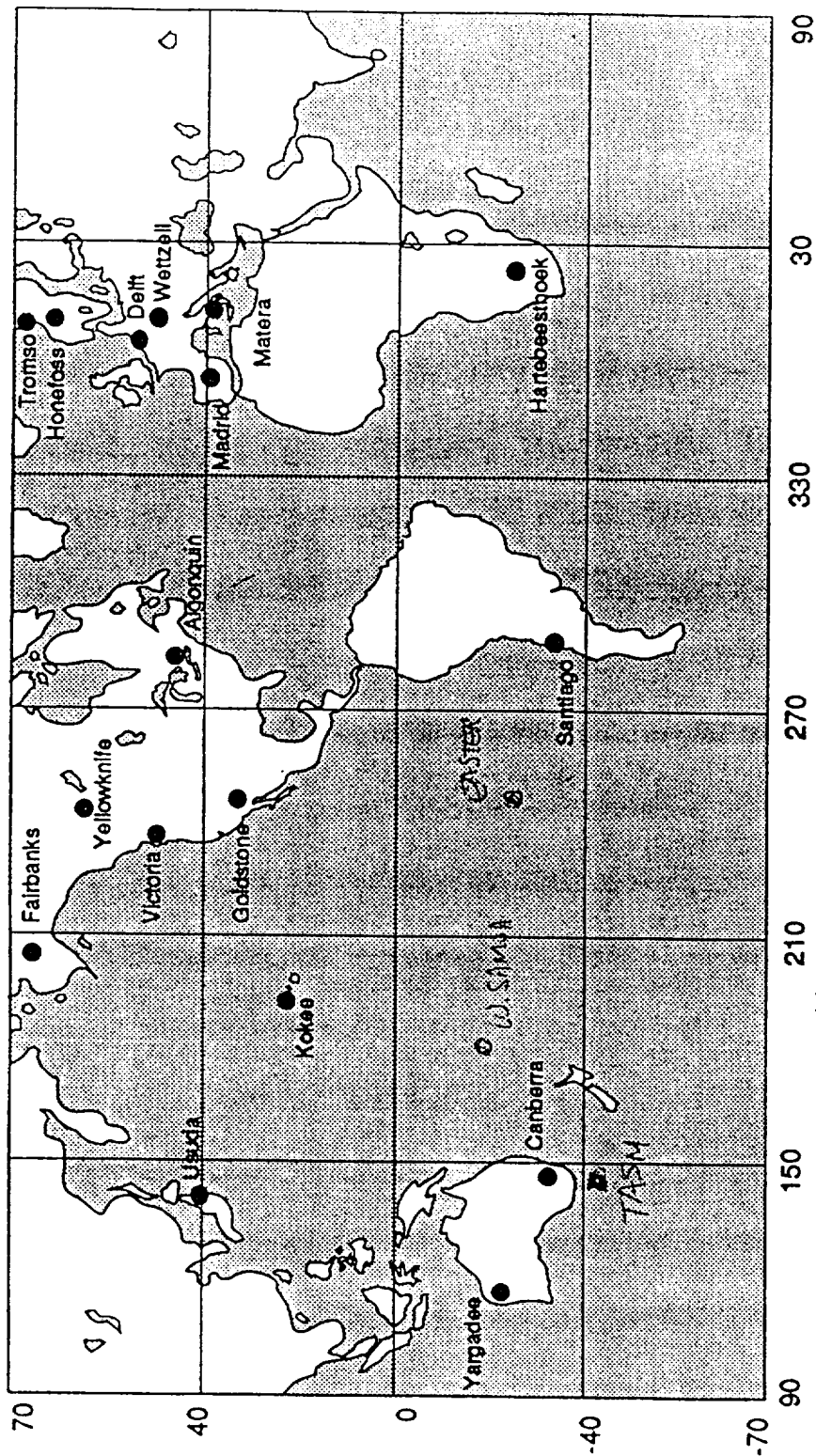
- Analyzed days 34-38 of GIG '91

- Data: 17 Rogue Sites

           Plus   Hobart mini-mac

                   W. Samoa TI

                   Easter I. TI

- Analysis Strategies

  - Fix Hobart Kokee and Wettzell to SV5

    - No a priori constraints on estimated parameters

    - Estimated baselines range from 800 km to 8000 km

    - Repeatability result: 20 PPB to 2 PPB

  - Adjust all stations with 1 meter a priori, all other estimated parameters have no a priori

  - Pole position error estimate (RMS): 1 mas

GIG 91 DATA

- All Rogue sites, except S. California array and Honefoss

- Augmented network

  - Hobart, Tasmania (Mini-Mac)

  - W. Samoa (TI-4100)

  - Easter Island (TI-4100)

GIG '91
GPS Experiment for IERS and Geodynamics
ROGUE RECEIVER LOCATIONS

ADDITIONAL ROGUES IN CALIFORNIA PERMANENT ARRAY:
PINON, SCRIPPS, JPL MESA

ANALYSIS

DAY	STATUS
34	✓
35	✓
36	✓
37	✓
38	✓
39	
40	
41	
42	
43	
44	

TEST
DATA
SET

DOUBLE DIFFERENCE RESIDUALS
OVER 24 HOUR PERIOD
DAY 86

PRN

PRN
23
22
21
20
19
18
17
16
15
14
13
12
11
9
8
6
3
2

WEEK 578 RESULTS
20 Stations; 15 Satellites

Day #	# of obs	# of passes	rms (cm)	No data from:	σ > 5 cm for:
34	11545	218	1.923	—	Usuda W. Samoa (4 cm) Hartebeestoek Easter Is. Santiago
35	11423	224	1.794	Madrid W. Samoa	Usuda Hartebeestoek Easter Is. Santiago
36	15036	291	1.906	—	Madrid Usuda (4.2 cm) Hartebeestoek Easter Is. Santiago
37	14902	290	1.861	Hartebeestoek	Usuda

REPEATABILITY BASED ON 4 DAYS
8 STA , 28 BASELINES

y = 3.2306e-2 + 3.8144e-9x

6.3 x10⁻⁹ without >10,000 km baselines

+ LENGTH (M)

LENGTH (M)

BSL. DIS (KM)

REPEATABILITY BASED ON 4 DAYS
8 STA, 28 BASELINES

$y = 3.6375e\text{-}2 + 2.91117e\text{-}9x$

5.0×10^{-9} without >10,000 km baselines

x VERT (M)

VERT (M)

BSL DIS (KM)

0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00

0   2000   4000   6000   8000   10000   12000   14000

Polar Motion Comparison During the GIG Campaign

Figure showing Delta xp (mas) vs MJD (48260 to 48320) with data series: Lageos, IRIS, CSR GIG, Bull B.

Polar Motion Comparison During the GIG Campaign

Figure showing Delta yp (mas) vs MJD (48260 to 48320) with data series: Lageos, IRIS, CSR GIG, BULL B.

GLOBAL GPS ORBIT DETERMINATION

B. Schutz, P. Abusali, M. Watkins,
H. Rim, and B. Tapley

Center for Space Research
The University of Texas at Austin

IAG
Vienna, Austria
August 1991

SUMMARY

- Analyzed days 34-38 of GIG '91

- Data: 17 Rogue Sites

  Plus Hobart mini-mac

        W. Samoa TI

        Easter I. TI

- Analysis Strategies

  - Fix Hobart Kokee and Wettzell to SV5

    - No a priori constraints on estimated parameters

    - Estimated baselines range from 800 km to 8000 km

    - Repeatability result: 20 PPB to 2 PPB

    - Adjust all stations with 1 meter a priori, all other estimated parameters have no a priori

    - Pole position error estimate (RMS): 1 mas

SOFTWARE VALIDATION

- **Force and Kinematic Models**

  - MSODP and MSODP1: Agree to sub-mm level over 7-day GPS arcs

  - MSODP1 and UTOPIA: Agree to mm level in all models (ROCK4 not tested, not available in UTOPIA)

  - UTOPIA and GEODYN (GSFC): Agree to mm level for TOPEX/POSEIDON (largest difference in ocean tide force model)

  - UTOPIA extensively used for SLR processing

  - Etalon analysis/models similar to GPS
    (fit 800 days of SLR Etalon data to few cm)

SOFTWARE VALIDATION (continued)

- ## GPS Measurement Model

  - Tests preprocessing system

  - Zero baseline tests of TI and Trimble

  - Short, calibrated baseline tests between Trimble, TI, TI-Trimble, TI-Minimac, and Trimble-Minimac

  - Comparisons of GPS results with VLBI and SLR (Recent: Onsala/Tromso, McDonald/Platteville/Quincy; results 1–2 parts in 10^8)

GEODETIC PROCESSING (COMPUTER: CRAY Y-MP)

- MSODP: Multi-Satellite Orbit Determination Program. Developed for GPS processing (planned to be phased out by end of 1991).

- MSODP1: Similar to MSODP, but includes high (GPS) and low (e.g., TOPEX) satellites. Will become primary processing software for multi-satellite data. Has more extensive force models, more compatible with UTOPIA, write regress files, etc.

- LLISS: Large Linear System Solver. Uses regress file (used for gravity estimation, etc.).

DATA PREPROCESSING (COMPUTER: VAX)

- Convert raw receiver binary or RINEX into VAX binary

- Review and correct receiver phase measurement time tags (EDORBCL)

- Insert information flags (PREPB)

- Edit phase, fix cycle slips (EDPH)

- Review double difference, perform further editing, write DD file (ASCII) (also preliminary geodetic analysis

- Utility programs (print binary file, edit binary flags, sample data, etc.)

GIG '91
GPS Experiment for IERS and Geodynamics
ROGUE RECEIVER LOCATIONS
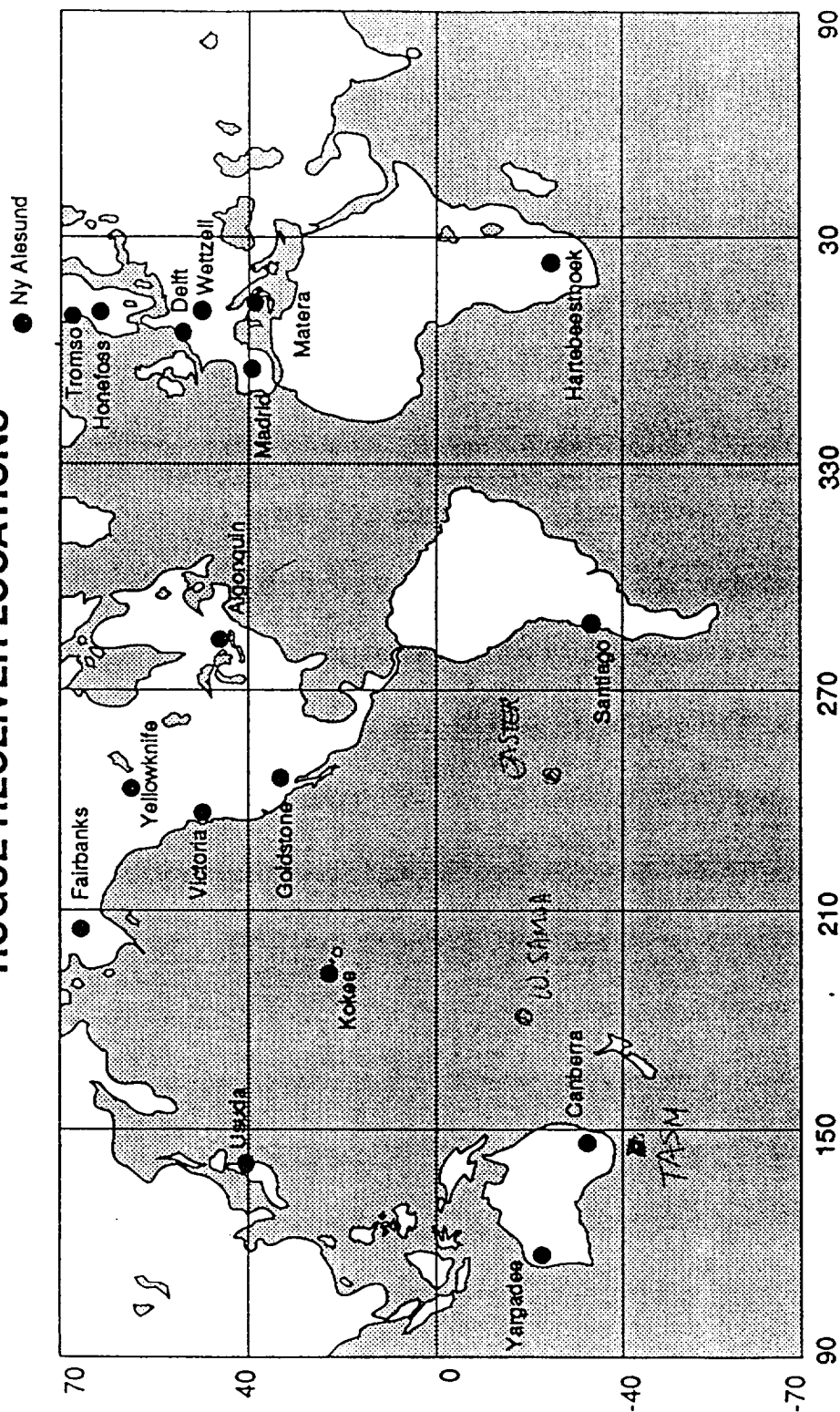
ADDITIONAL ROGUES IN CALIFORNIA PERMANENT ARRAY:
PINON, SCRIPPS, JPL MESA

GIG 91 DATA

- All Rogue sites, except S. California array and Honefoss

- Augmented network

  - Hobart, Tasmania (Mini-Mac)

  - W. Samoa (TI-4100)

  - Easter Island (TI-4100)

ANALYSIS

DAY	STATUS
34	✓
35	✓
36	✓
37	✓
38	✓
39	
40	
41	
42	
43	
44	

TEST DATA SET

DOUBLE DIFFERENCE COVERAGE
OVER 24 HOUR PERIOD
DAY 36

PRN

| 23 |
| 22 |
| 21 |
| 20 |
| 19 |
| 18 |
| 17 |
| 16 |
| 15 |
| 14 |
| 13 |
| 12 |
| 11 |
| 9 |
| 8 |
| 6 |
| 3 |
| 2 |

GPS ANALYSIS MODELS

	MSODP1/LLISS	MSODP
• Gravitational Model		
• GM =	398600.4404 km/s	398600.436
• Nominal field:	TEG-2 (Tapley, et al.)	GEM-T1
• Truncation of field:	8x8	Same
• Point mass Sun and Moon		Same
• Solid Tide:	degree 2	Same
• Ocean Tide:	Not included	Same
• Central body relativistic perturbation		Same
• Nongravitational Model		
• Solar Radiation (ROCK4)		Same
• y-bias		Same
• Earth Radiation:	Not included	Same
• Empirical Forces:		
• Along track (CT)		No
• Radial (once/rev)		No
• Normal (once/rev)		No

GPS MODELS (continued)

MSODP1/LLISS

MSODP

- Reference Frame (a priori)

- Station coordinates: SV5

Same

- IERS Standards: precession/nutation

Same

- IERS Standards: plate motion (AM0-2)

Same

- IERS Standards: solid tides/loading

Same

- Lageos pole position (x,y)

Same

- Lageos/VLBI UT1
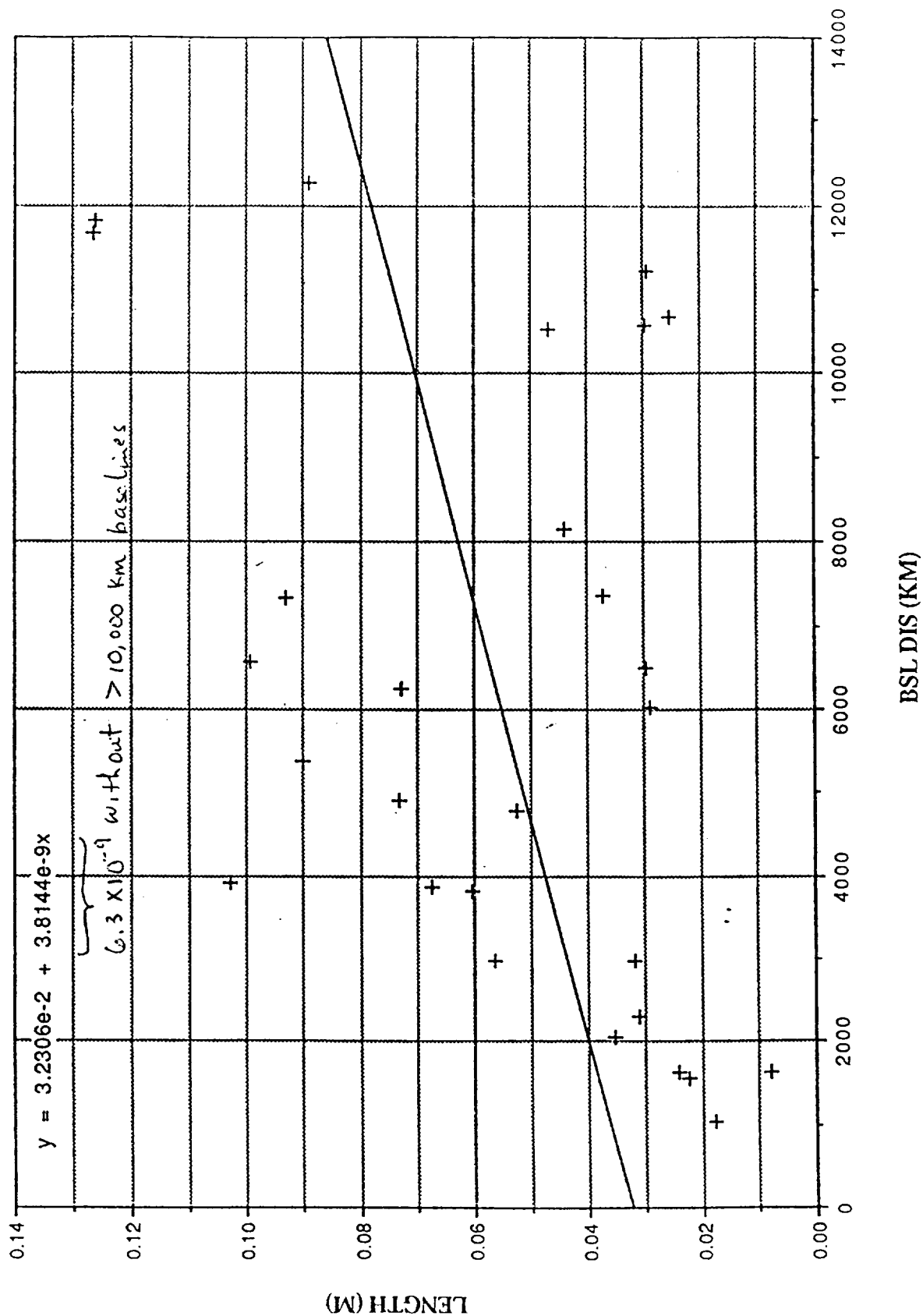
Same

WEEK 578 RESULTS
20 Stations; 15 Satellites

Day #	# of obs	# of passes	rms (cm)	No data from:	σ > 5 cm for:
34	11545	218	1.923	—	Usuda W. Samoa (4 cm) Hartebeestoek Easter Is. Santiago
35	11423	224	1.794	Madrid W. Samoa	Usuda Hartebeestoek Easter Is. Santiago
36	15036	291	1.906	—	Madrid Usuda (4.2 cm) Hartebeestoek Easter Is. Santiago
37	14902	290	1.861	Hartebeestoek	Usuda
38					

REPEATABILITY BASED ON 4 DAYS
8 STA , 28 BASELINES

+ LENGTH (M)

$y = 3.2306e\text{-}2 + 3.8144e\text{-}9x$

6.3×10^{-9} without >10,000 km baselines

LENGTH (M)

BSL DIS (KM)

REPEATABILITY BASED ON 4 DAYS
8 STA, 28 BASELINES

y = 3.6375e-2 + 2.9117e-9x

6.0×10^{-9} without >10,000 km baselines

x VERT (M)

VERT (M) (vertical axis, values: 0.00, 0.02, 0.04, 0.06, 0.08, 0.10, 0.12, 0.14)

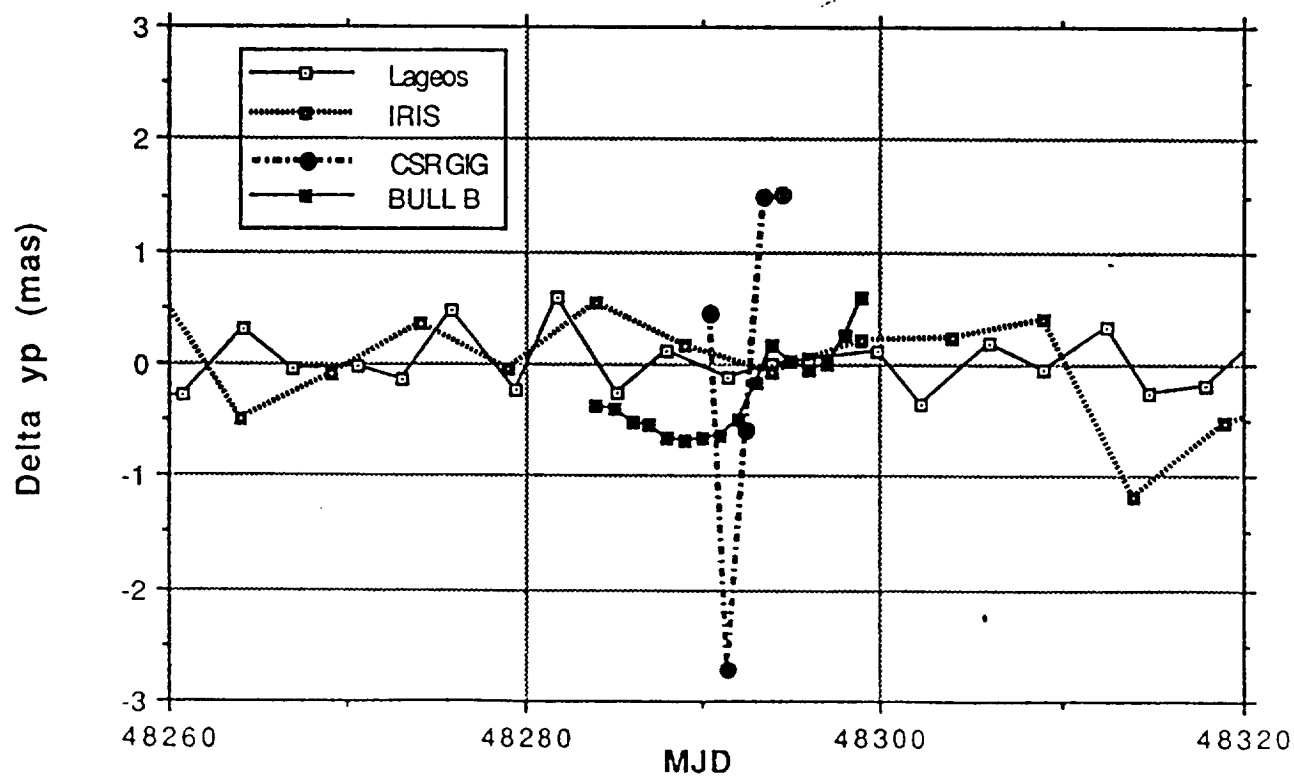**BSL DIS (KM)** (horizontal axis, values: 0, 2000, 4000, 6000, 8000, 10000, 12000, 14000)
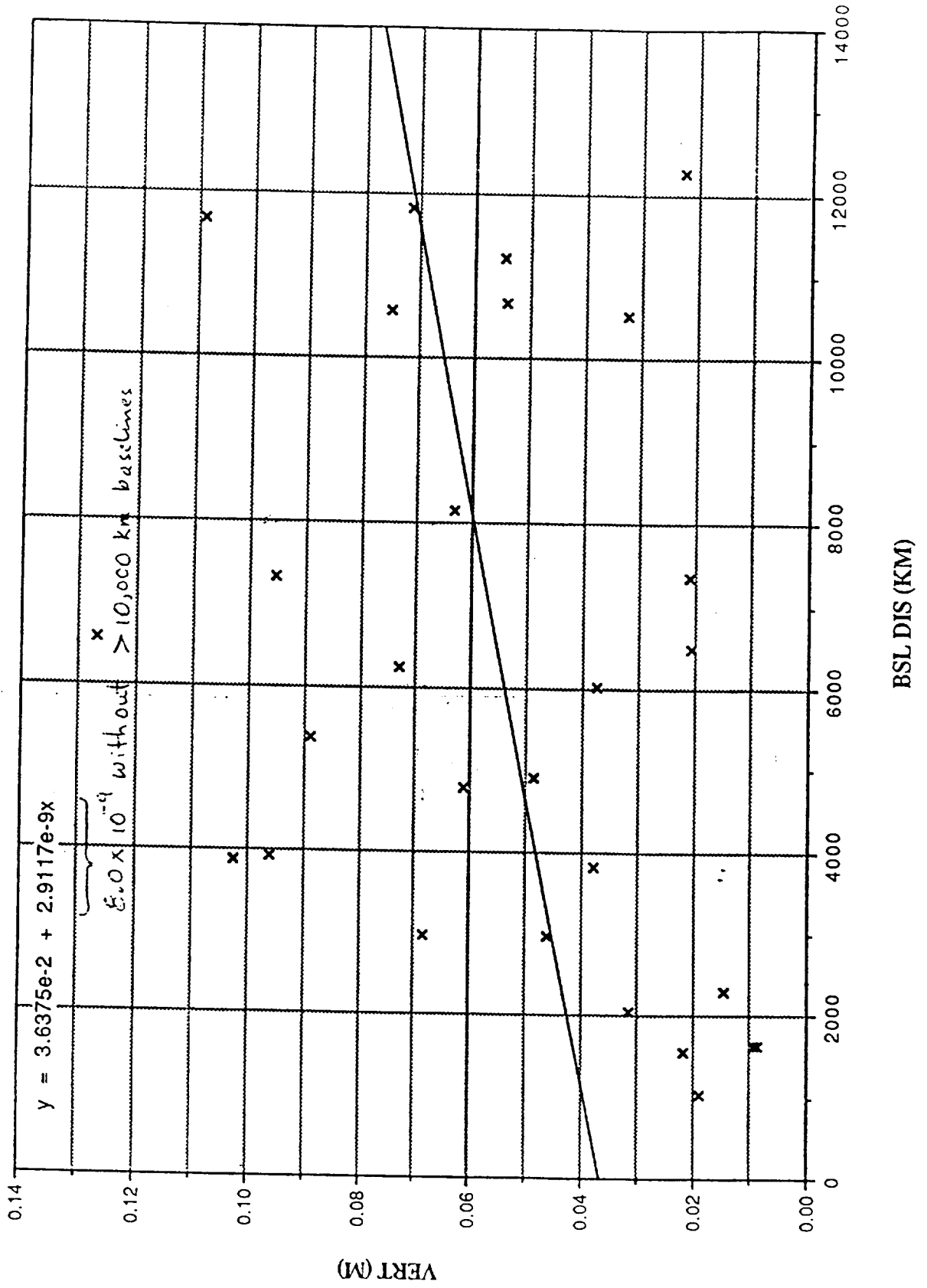
Polar Motion Comparison During the GIG Campaign
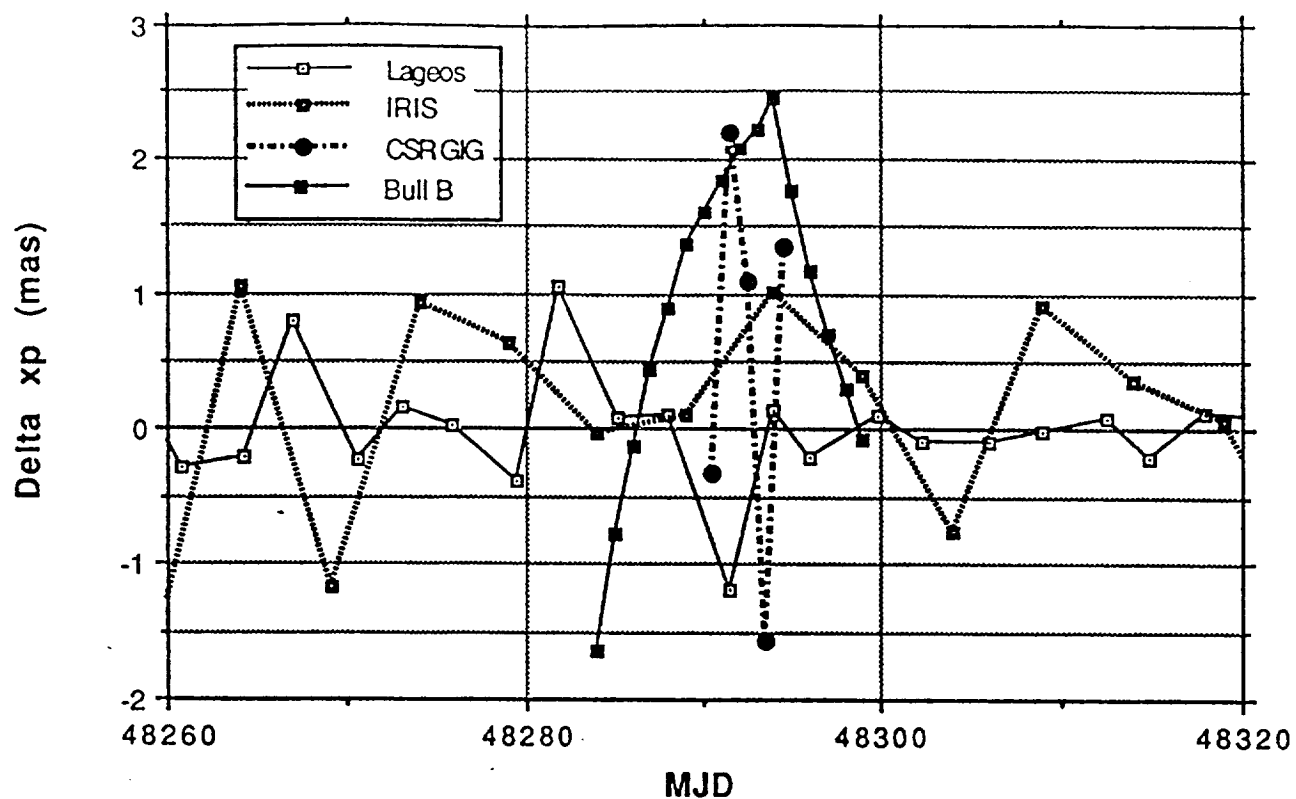
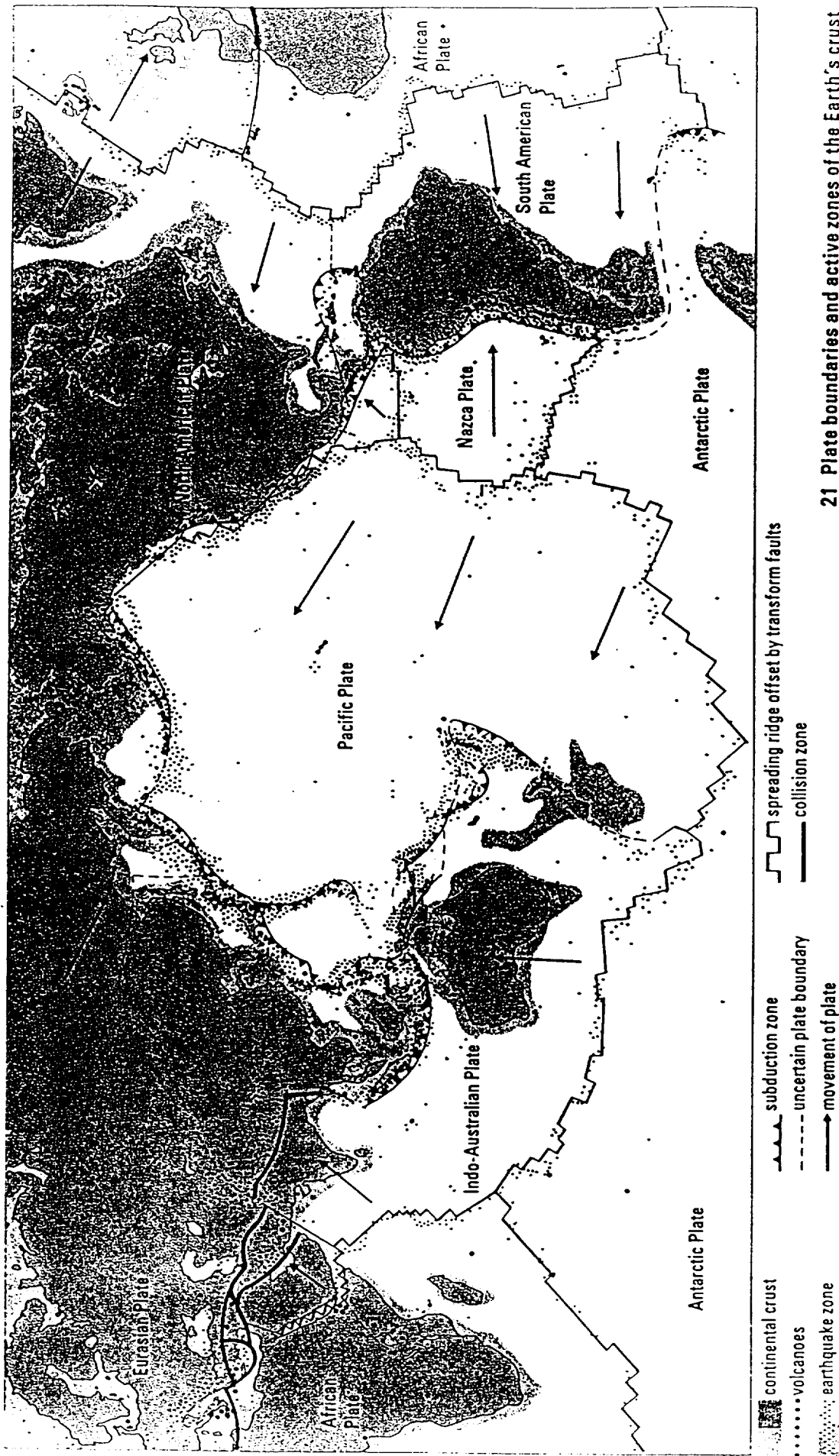Polar Motion Comparison During the GIG Campaign

GEODETIC ANALYSIS OF GPS MEASUREMENTS NEAR THE TONGA TRENCH: 1988-1990

B. Schutz, D. Kuang, P. Abusali, F. Taylor
The University of Texas at Austin

M. Bevis
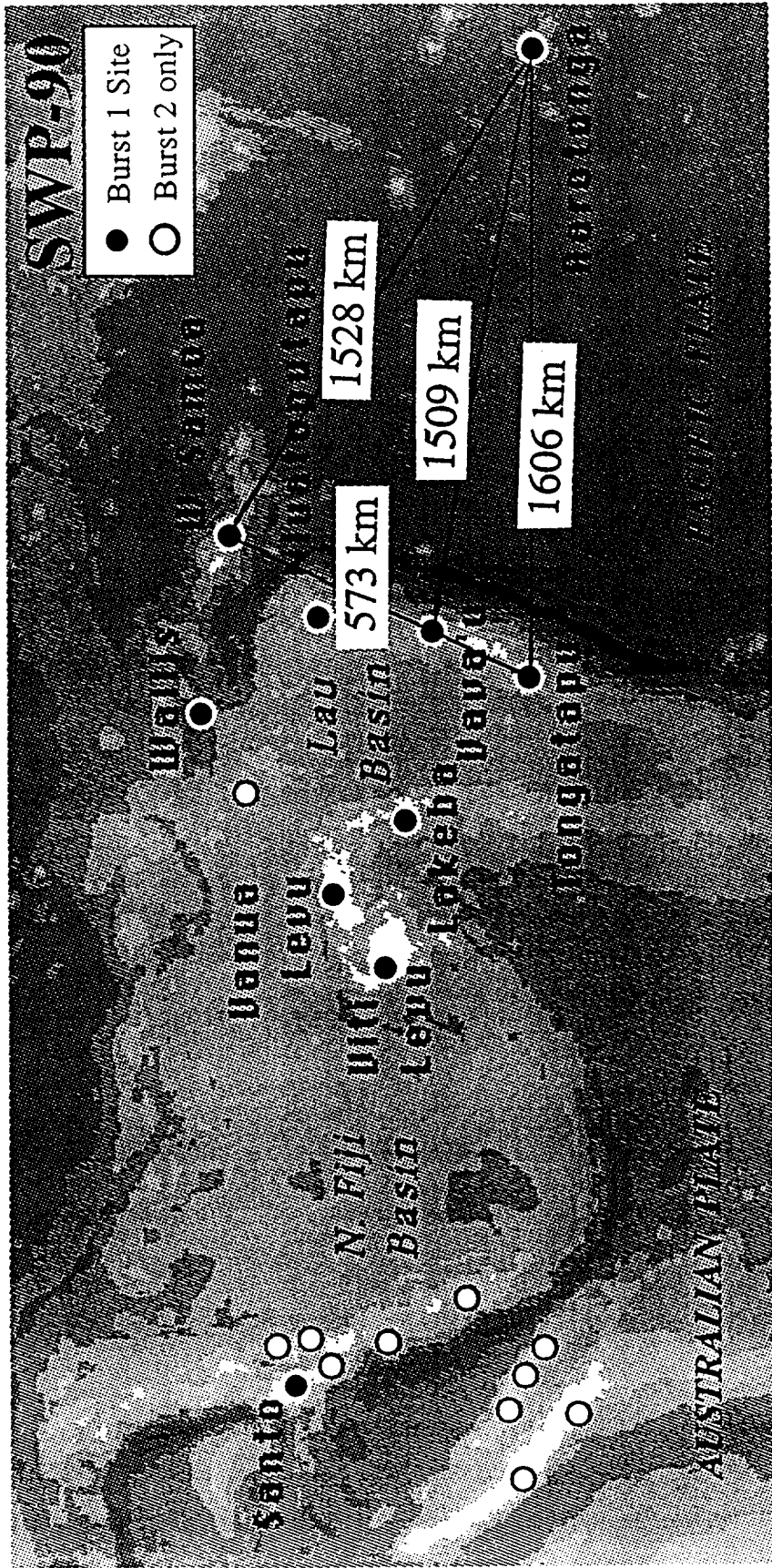North Carolina State University

AGU

DECEMBER 1991
SAN FRANCISCO

21 Plate boundaries and active zones of the Earth's crust

Labels on map:

African Plate

South American Plate

Nazca Plate

Antarctic Plate

Pacific Plate

Indo-Australian Plate

Antarctic Plate

Eurasian Plate

African Plate

Legend:

continental crust

volcanoes

earthquake zone

subduction zone

uncertain plate boundary

movement of plate

spreading ridge offset by transform faults

collision zone

SWP-90

● Burst 1 Site
○ Burst 2 only

1528 km

1509 km

1606 km

573 km

Wallis

Lau
Basin

Vanua
Lebu

Viti
Lebu Lakeba

Tongatapu

N. Fiji
Basin

Santo

AUSTRALIAN PLATE

PACIFIC PLATE

SOUTHWEST PACIFIC DATA CHARACTERISTICS

- 1988:

  Fiducial: TI-4100 (8 sites), Mini-Mac (1 site)

  SWP Network: TI-4100 (4 sites)

  SA off, 11 day campaign, 7 satellites

- 1989 (Session 1):

  Fiducial: Mini-Mac (5 sites), TI-4100 (10 sites), Trimble SLD (3 sites)

  SWP Network: TI-4100 (5 sites), Trimble SLD (3 sites)

  SA off, 5 day campaign, 7 satellites

- 1990 (Burst 1):

  Fiducial: Mini-Mac (6 sites), Trimble SST(5), TI-4100 (4), Rogue (5)

  SWP Network: Trimble SST (11 sites)

  North American Evaluation Network: Trimble SST & TI-4100 (3 sites)

  SA on, 8 day campaign, 13 satellites

SOUTHWEST PACIFIC PROCESSING STATUS

- 1988:

  Processing complete (11 days); various experiments in progress

- 1989 (Session 1):

  Processing in progress; processing of Sessions 2-4 completed to establish DMA Smithfield coordinates in reference frame

- 1990 (Burst 1):

  Processing complete (except DMA data); various experiments in progress

GPS ANALYSIS MODELS

MSODP Force Models

MSODP Reference Frame

- Gravitational Model
  - GM = 398600.440 km/s
  - Nominal field: GEM-T1
  - Truncation of field: 8x8
  - Point mass Sun and Moon
  - Solid Tide: degree 2
  - Ocean Tide: Not included
  - Central body relativistic perturbation

- Nongravitational Model
  - Solar Radiation (ROCK4)*
  - y-bias*
  - Earth Radiation: Not included

- Fixed station coordinates
  - Combined SLR/VLBI
    - SLR: CSR91L03
    - VLBI: GSFC GLB718
    - Epoch: January 1988
  - Coordinates mapped to campaign epoch using SLR or VLBI observed velocities

- IERS Standards:
  - Precession/nutation
  - Solid tides/ocean loading

- Earth Rotation
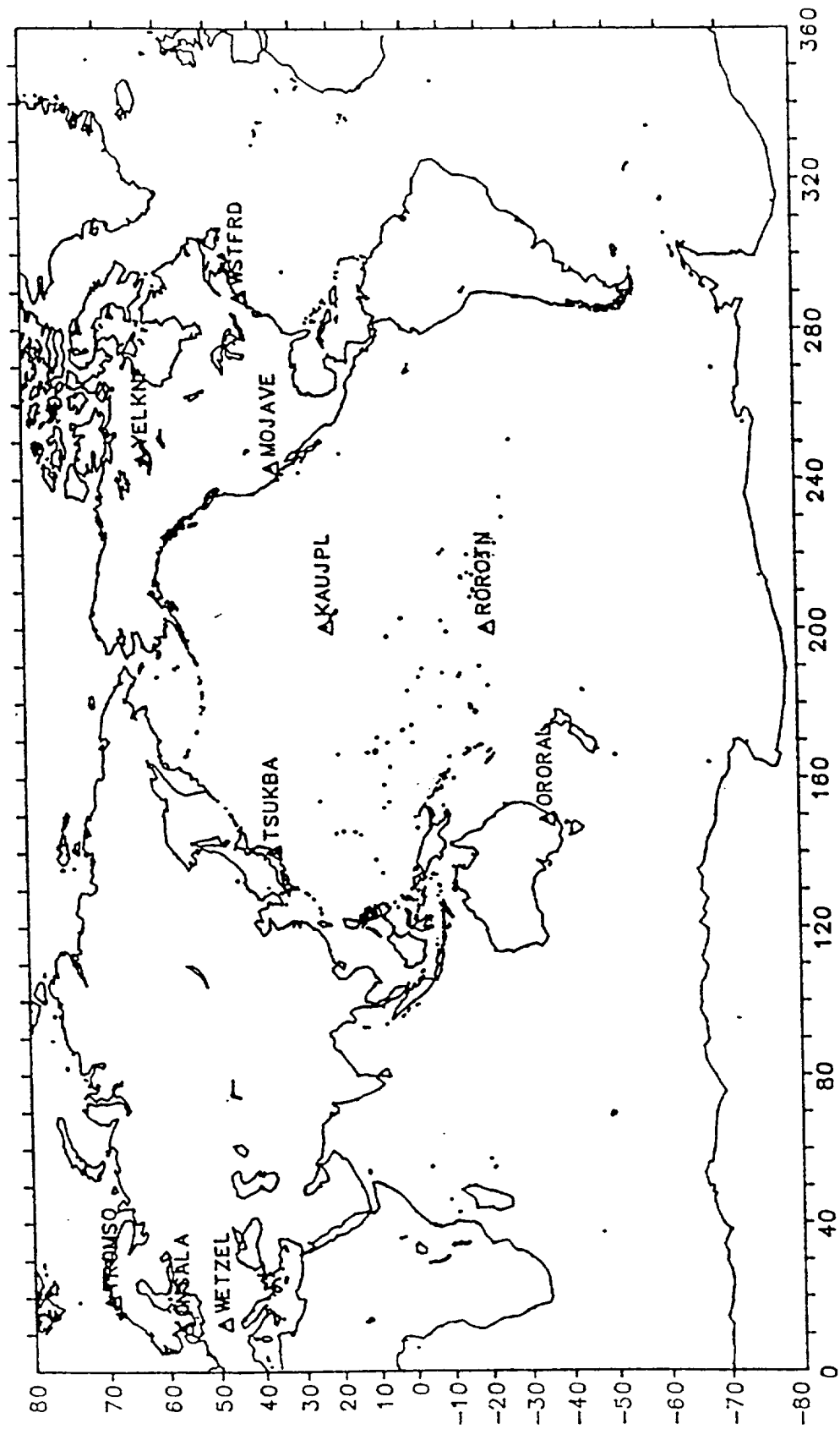 - Lageos pole position (x,y)
  - Lageos/VLBI UT1

* Denotes solve-for parameter

Figure 2. 1988 Southwest Pacific Campaign Global Sites

SWP-90 ANALYSIS STRATEGY AND EXPERIMENTS

- Global fiducial network to determine orbits

- Multi-day (7 day) arcs

- Simultaneous adjustment of orbit parameters (including force model parameter), 2.5 hour zenith delay, ambiguity parameters, station coordinates; all estimated parameters have infinite a priori covariance

- Experiments:
- Full global network solution (selected fixed sites)

  Number of Double Differences (DD): ~ 326,000
  DD RMS: 2.5 cm

- Reduced network solution: emulate the network configuration in 1988

  Number of Double Differerences (DD): ~ 154,000
  DD RMS: 2.9 cm

SWP-90 SOLUTIONS

- Full global network fixed sites:
  Minimac: Mojave, Westford, Richmond, Wettzell, Tasmania

- Reduced network fixed sites:
  Mojave, Westford, Wettzell, Orroral (Trimble)

- Comparison between full network and reduced network:

Baseline	Global (m)	Reduced (m)
Rarotonga/Vava'u (1509180+)	0.7633 (.025)	0.7724 (.026)
Rarotonga/Tongatapu(1605587+)	0.9078 (.025)	0.9206 (.027)
Rarotonga/W.Samoa(1527538+)	0.6459 (.017)	0.6574 (.018)
(Repeatability RMS in parentheses)		

- Precision estimate:
  • From above 3 lines: 10-20 parts per billion
  • From 103 lines in the global network: 2.3 cm + 8 ppb*length

SWP-90 EVALUATION SOLUTIONS

- Based on results from full global network:

Baseline	SWP-90	SLR/VLBI
Ororal (Tr)/Tasmania (MM) (805722+)	0.200	0.214
Kokee Park (Tr)/Huahine (Tr) (4312837+)	0.388	0.333
Mojave (MM)/McDonald Obs.(Tr) (1305503+)	0.619	0.625
Wettzell (MM)/Onsala (TI) (919659+)	0.478	0.449

(All distances in meters)

- Accuracy estimate: .10-30 parts per billion
  - Receiver mix used in evaluation
  - Evaluation sites include mix of SLR and VLBI

SWP-88 SOLUTIONS

- Fiducial sites (all TI-4100):
  Orroral, Kokee Park, Mojave, Westford, Richmond, Yellowknife, Wettzell, Onsala, Tromso

- Fixed sites:
  Orroral, Mojave, Westford, Wettzell

- Strategy:
  - Multi-day arcs: separate arcs for GPS Week 444 and Week 445 (July 1988)
  - Simultaneous adjustment of orbit and geodetic parameters (as in 1990)

- Solution characteristics:
  - Week 444: 73710 DD, RMS = 2.3 cm
  - Week 445: 43147 DD, RMS = 2.1 cm
  - Repeatabilities (combined 444 and 445):
    - Rarotonga/Tongatapu: 4.6 cm
    - Rarotonga/Vava'u: 4.1 cm
    - Rarotonga/W. Samoa: 6.9 cm

CONCLUSIONS

- SWP-90:
  - Solution has precision at level of 10 to 20 ppb
  - Comparison with SLR/VLBI baselines in Australia, French Polynesia, North America and Europe indicates agreement at the 10-20 ppb level
  - Results from global network of 20 sites compared with results of a reduced network to emulate 1988 fiducial configuration: agreement within precision estimate

- SWP-88:
  - Solution based on 7 Block I satellites, TI-4100 receivers (maximum 4 satellites)
  - Experiments using two separately edited data sets from Week 444 show differences at the repeatability level
  - 1988 results exhibit higher daily repeatability than 1990 (~ 4.5 cm vs. ~2.5 cm)
  - Comparison with VLBI baseline Wettzell/Tromso shows agreement at 10 ppb (Baseline: 2296 km)

- SWP-89:
  - In progress

GPS ORBIT ACCURACY

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ABSTRACT

Previous analysis of GPS data collected by special campaigns (e.g., CASA UNO, GIG-91, etc.) has shown that the satellites exhibit somewhat different characteristics, especially between the eclipsing and non-eclipsing satellites. Using the GIG-91 data which provided a reasonable global distribution of stations, the influence of unmodeled orbital effects has been examined using double differenced carrier phase data. While there is evidence that suggests the unmodeled orbital effects are not a limiting factor in achieving a part in 10^8 level in baseline results, these components may be factors in reaching a part in 10^9. Experiments with the GIG data set include comparison with other ephemerides and the estimation of empirical parameters for the purpose of improving the model error characterization.

1. INTRODUCTION

Previous results have shown that unmodeled forces exist when the GPS satellites are in eclipse season, i.e., the period during which the satellite experiences the umbra/penumbra of either the Earth or the Moon [Schutz et al., 1991; Fliegel et al., 1992; Gouldman et al., 1989]. Possible contributors to the observed effects include the proper representation of the discontinuity associated with the shadow boundary and the implementation of appropriate adjustments in the numerical integration algorithm [Lundberg et al., 1991]. However, studies of this effect by Feulner et al.[1990] demonstrate that, while the effect can be significant, it does not account for most of the observed effect. Another effect that is associated with thermal radiation imbalance was examined by Vigue et al.[1991] who demonstrated that the effect should be observable.

The objective of this investigation was to assess the GPS orbit accuracy and to examine possible parameterization to account for observed mismodeling of the measurements. Such an examination cannot be accomplished with a regional network, and is best suited for a global tracking network. The global data set of the GIG-91 Campaign [Melbourne, 1992] offers an opportunity to examine a variety of aspects concerning the fidelity of the GPS force, kinematic and measurement models. The campaign used about 20 Rogue P-code receivers plus several TI-4100 P-code receivers and numerous codeless receivers.

2. DATA AND MODELS

The software used for the data analysis was the set of programs know collectively as TEX-GAP, described by Schutz et al.[1992]. For the results of this paper, ionospherically corrected

phase measurements were used in a double difference mode.

The specific receivers used in the analysis were 17 Rogue receivers plus TI-4100 receivers in the Pacific to provide improved global coverage, as given in Table 1. The GPS force models followed the current IERS Standards [McCarthy, 1989] and scale factors on the ROCK4 [Fliegel, 1992] and y-bias parameters were estimated. The Chao [1974] troposphere model was used. Lageos-derived polar motion and UT1 were used as a priori. Pseudo-range measurements were used to verify and/or correct the respective receiver clocks. The reference frame is given by Schutz et al.[1992].

For this study, data from GPS Weeks 578 and 579 (days 34 to day 41, inclusive) were used. All available satellites (5 Block I and 10 Block II) were included in the analysis.

3. ESTIMATION STRATEGIES

All results were obtained using multi-satellite versions of UTOPIA, known as MSODP. The estimation process is based on a batch algorithm, using Givens rotations to solve the least squares problem. For the results, three sites were fixed (Goldstone, Wettzell, and Hobart) and the remaining 17 sites were adjusted. For each arc, satellite position and velocity were estimated at the initial time point of the arc, a solar radiation pressure scale factor and a y-bias were estimated. Zenith delay parameters were estimated at 2.5 hour intervals and phase ambiguities were estimated on each pass. In all cases, the a priori covariance was assumed to be infinite, thus allowing all parameters to freely adjust.

Alternate empirical forces were introduced for some cases. These forces include radial, along-track and cross-track components represented by a periodic function. The period of this function was adopted to be the orbital period, thus the empirical force accommodated once/revolution effects. The estimated parameters were amplitude and phase of the function.

The arc lengths included a series of "short arcs" of one-day duration, each of which was independent of the other arcs. For this study, a "long arc" consisted of a 5-day arc in which a single set of orbital parameters for each satellite were estimated. For the one-day arcs, three cases have been examined:

• Case 1: estimate ROCK4 scale parameter and y-bias for each satellite
• Case 2: estimate coefficients of once/revolution radial, transverse and normal perturbations instead of radiation pressure and y-bias
• Case 3: same as Case 2 except a constant along-track perturbation was estimated instead of the once/revolution transverse force

For the 5-day arc, a strategy similar to Case 1 was followed except that two y-bias parameters for each satellite were estimated.

4. RESULTS

The statistics of the Case 1 results are shown in Table 2. In general, the RMS of the double

difference residuals from the one-day arcs were in the range of 1.2 to 1.6 cm. Examination of the raw phase measurements suggests that the ionosphere corrected phase measurement has a precision of about 0.3 to 0.4 cm, thus leading to the conclusion that the precision of the double difference (DD) measurement should be about 0.6 to 0.8 cm. The discrepancy between the DD precision estimate and the values in Table 2 is indicative of one aspect of mismodeling. However, it cannot be concluded that the discrepancy is caused completely by orbit mismodeling and the possibility that measurement systematics, such as multi-path, are a contributor must be considered.

The increased DD RMS from the 5-day arc, however, is indicative of a level of orbit model error since the measurement systematics are not dependent on the arc length, but force models are significantly dependent on the arc. Nevertheless, although the 5-day arc should use daily sub-arc values of SRP and y-bias to more nearly match the one-day arcs, past experience has shown that such representations do not substantially reduce the RMS on the long arc [Schutz et al., 1990].

There are possible sources of orbital mismodeling: gravitational and nongravitational. Experience with satellite laser range (SLR) measurements to the Etalon satellites, however, suggests that no significant gravitational mismodeling exists [Eanes, et al., 1991]. The two Etalon satellites were launched into GLONASS-like orbits by the USSR in 1989. Both are spherical, with a reasonably low area to mass ratio. The dominant model error on the Etalon satellites is nongravitational in origin, however, the nature of the nongravitational effects on Etalon is quite different than GPS and the Etalon experience cannot be extrapolated to GPS (or GLONASS). Concerning the gravitational contributions, the fact that the GPS satellites are in "deep resonance" distinguishes them from the Etalon satellites which are not; thus, there is still the possibility of a gravitational effect, but it is most likely of very long period and would not be evident in arcs with a duration of several days.

The mismodeling is further evidenced by discontinuities in the common time point between the one-day arcs. For PRN-3, the differences between the Case 1 one-day arcs and the 5-day arcs is shown in Fig. 1 for the radial, along-track and cross-track components. As shown, the discontinuities at the common time point are several meters in some cases, while others are at the level of 2 meters. The discontinuities are associated with mismodeling on the one-day arcs, however, the magnitude of the discontinuity is, in part, determined by the mismodeling on the 5-day arc. Note that the magnitudes of discontinuities in the radial and cross-track directions are much smaller than those in the along-track direction.

For PRN-3, the 5-day arc was compared with the ephemeris produced by Defense Mapping Agency. The differences are shown in Fig. 2. This comparison was accomplished without any adjustment to either the DMA or the UT ephemerides, and was formed by directly differencing the two ephemerides in the Earth-fixed system and transforming the difference into radial, along-track and cross-track components. Because of the difference in GM used in the ephemerides (DMA: 398600.5; UT: 398600.441 km^3/s^2), a radial bias exists at the meter level. The periodic differences probably reflect model differences, including reference frame differences. Since the two cases were generated by independent software and different global tracking networks as well as different data types, the differences can be regarded as an indication of the level of GPS orbit accuracy. The RMS of differences are 1.6 m radial, 2.3 m along-track and 2.6 m cross-track. The size of the cross-track in comparison to the along-track is an indication of reference frame differences.

Additional experiments using the once/revolution force model characterizations were conducted. The Case 3 result for PRN-3 is shown in Fig. 3 for the coefficients of the radial and cross-track components and the constant (over one day) along-track component is shown in Fig. 4, including the formal error of the respective daily estimates. Although the trends exhibited by these parameters appear to be systematic, it should be noted that the effect on the RMS of the one-day arcs has been small. Further experiments will be conducted using these parameterizations in long arcs.

5. CONCLUSIONS

Based on analysis of the GIG-91 data set, double difference phase residual RMS at the 1.2 to 1.6 cm level have been obtained for one-day arcs, while a 5-day arc shows 3.8 cm. The one-day arcs are probably influenced by both unmodeled forces on the GPS satellites and by systematic measurement model errors, while the 5-day arc is expected to be dominated by force model errors. Experience with other satellites at similar altitudes suggests the dominant force model error has a nongravitational origin. Comparison of the one-day arcs with the five-day arc shows discontinuities at the common time point of the one-day arcs with differences of several meters. Direct comparisons with DMA ephemerides show differences at the 2 to 3 meter level (RMS), thus providing an indication of the orbit accuracy over days 34-38. Use of empirical force models as a means of investigating the nature of possible model errors was applied to one-day arcs, with results that exhibit systematic characteristics. Future studies will investigate these parameterizations.

6. ACKNOWLEDGEMENTS

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Gouldman, M., B. Hermann, D. Weedon, Evaluation of GPS production ephemeris and clock quality, *Proceedings of the Fifth International Geodetic Symposium on Satellite Positioning, Las Cruces*, pp. 210-222, 1989.

Lundberg, J., M. Feulner, P. Abusali, and C. Ho, Improving the numerical integration solution of satellite orbits in the presence of solar radiation pressure using modified back differences, AAS Preprint 91-187, presented at the AAS/AIAA Spaceflight Mechanics Meeting, Houston, 1991.

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Schutz, B., C. Ho, P. Abusali and B. Tapley, CASA UNO GPS orbit and baseline experiments, *Geophys. Res. Letters, Vol. 17(5)*, pp. 643-646, 1990.

Schutz, B., B. Tapley, P. Abusali and C. S. Ho, Accuracy assessment of GPS satellite orbits, *Adv. Space Res. Vol. 11 (6)*, pp. 189-196, 1991.

Schutz, B., P. Abusali, H. Rim, M. Watkins, D. Kuang and B. Tapley, GPS reference frames and Earth rotation, paper presented at the Sixth International Geodetic Symposium on Satellite Positioning, Ohio state University, March 1992.

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TABLE 1. GIG-91 SITES

Rogue Receivers:

Yaragadee, Australia	Wettzell, Germany
Canberra, Australia	Madrid, Spain
Santiago, Chile	Matera, Italy
Hartebeesthoek, S. Africa	Kootwijk, Netherlands
Kokee Park, Hawaii,	Ny Alesund, Norway
Usuda, Japan	Tromso, Norway
Goldstone, CA	Algonquin, Ontario
Victoria, BC	Yellowknife, NWT
Fairbanks, Alaska	

Minimac 2816AT Receiver:
    Hobart, Tasmania, Australia

TI-4100 Receivers:
    W. Samoa
    Easter Island

TABLE 2. ARC STATISTICS

One-Day Arcs

Day	Passes	DD Observations	RMS (cm)
34	221	11545	1.550
35	224	11421	1.511
36	291	15035	1.516
37	287	14823	1.396
38	280	13792	1.377
39	289	12397	1.378
40	304	13383	1.265
41	312	13742	1.204

Five-Day Arc

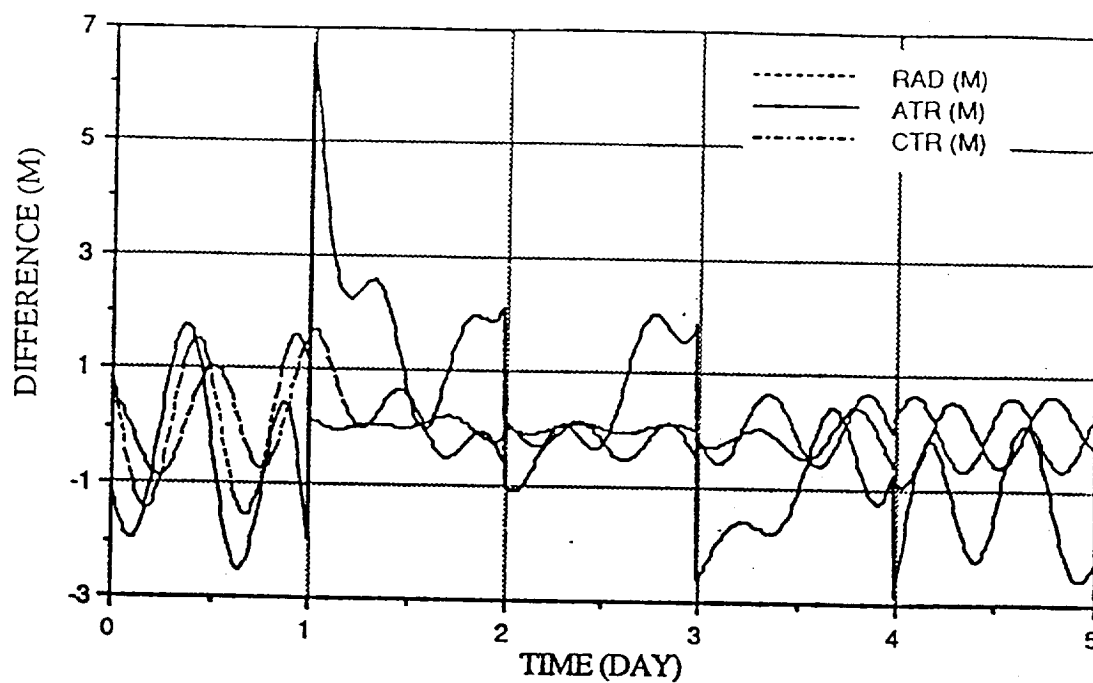|			
34-38	1300	66629	3.857

DD denotes Double Difference

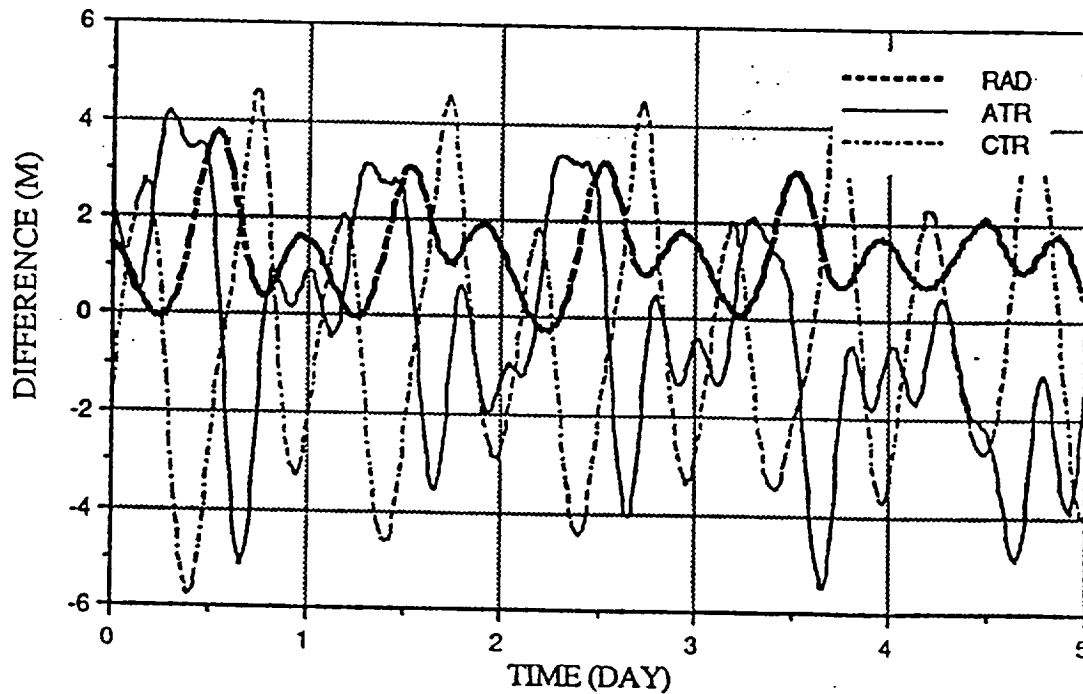Figure 1. Difference between 5-day and 1-day arcs of PRN03 for Case 1; Epoch: Feb.3, 1991.

Figure 2. Difference between UT/CSR 5-day arc and DMA ephemeris of PRN03; Epoch: Feb.3, 1991.
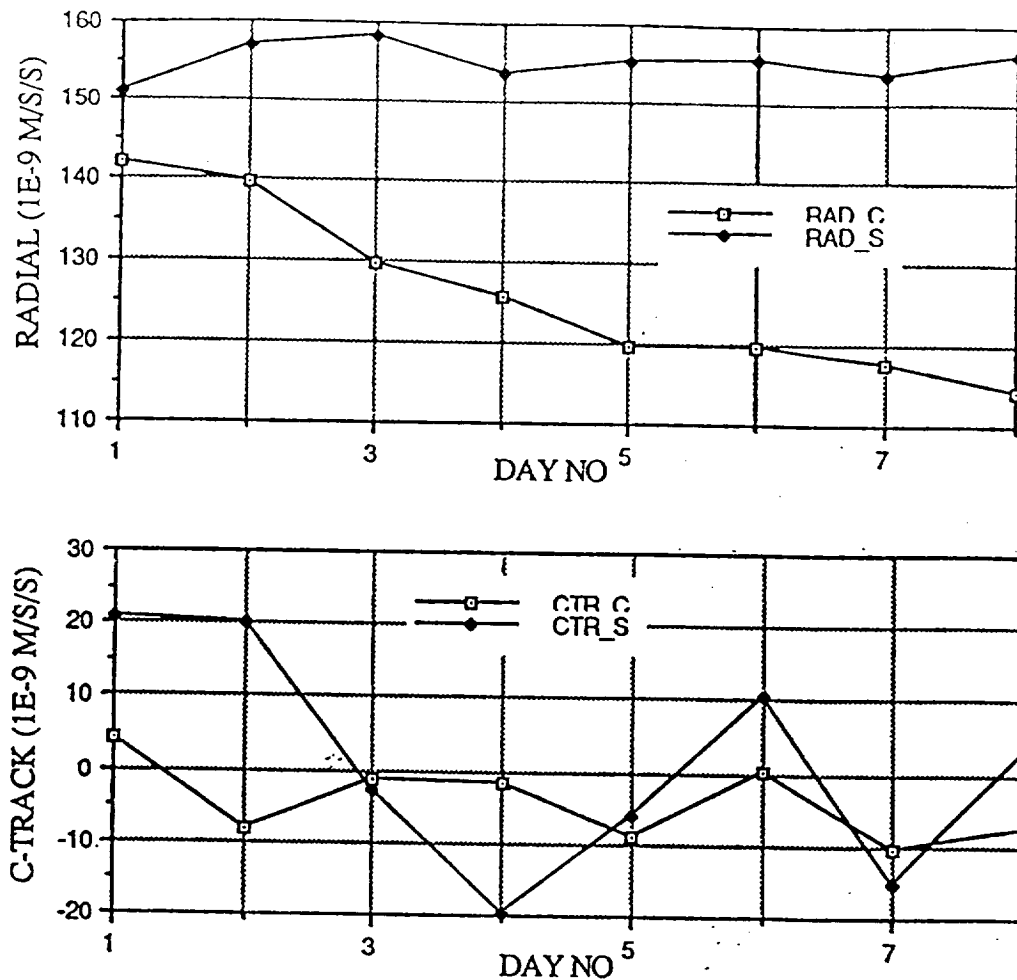
Figure 3. Estimated coefficients of once/rev radial and cross-track empirical acceleration for eight daily arcs of PRN03. Day No.1 is Feb.3, 1991.
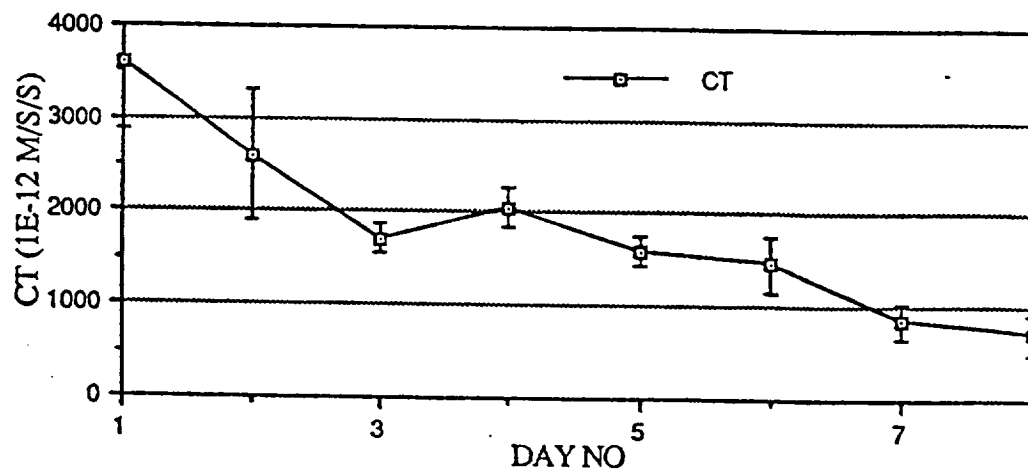

Figure 4. Estimated constant along-track empirical acceleration (Case 3) for eight daily arcs of PRN03. Day No.1 is Feb.3, 1991.

GPS REFERENCE FRAMES AND EARTH ROTATION

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ABSTRACT

With the forthcoming International GPS Service (IGS) campaign scheduled for June 21, 1992 to September 21, 1992, and with the expectation that Analysis Centers will provide products within two weeks of the collected data, an examination of strategies for the generation of potential products is appropriate. The primary products of the IGS are GPS ephemerides, Earth rotation, baselines and reference frame information. This paper describes an analysis of GIG-91 data for the purpose of examining strategies for the generation of IGS products. Preliminary results from the studies has shown agreement with Lageos Earth rotation results at the 0.8 mas and 1.0 mas levels in pole position (x,y), respectively. Other strategies have produced results at the 1.5 mas level. Comparison of selected baselines with those obtained in other campaigns has shown agreement at the level of 10 ppb, and agreement with baselines determined by VLBI at the several ppb level.

1. INTRODUCTION

In January and February, 1991, one of the most ambitious global GPS campaigns to date was undertaken, known as GIG-91. This campaign [Melbourne, 1992] included a variety of receivers in most areas of the world. For the first time, almost 20 high quality Rogue P-code receivers were used at global sites. In some sense, the GIG-91 was a precursor for the 1992 IGS Campaign, which will commence on June 21 and end on September 21. An additional campaign, known as EPOCH '92, centered on August 1, will provide an opportunity for a variety of regional activities. The IGS concept is described by Mueller and Beutler[1992].

Potential products of the IGS have been extensively discussed and the report of a panel charged to identify those products and the timely availability is given by Schutz et al. [1991]. In summary, the panel noted that Earth rotation, GPS ephemerides and reference frame/baselines would be products with the widest utility. Timeliness of the products was deemed important and the expectation that some products could be available within a few days to a few weeks was noted.

With this background, the primary purpose of this paper was to conduct experiments using the GIG-91 data set to evaluate estimation strategies that could be used in the IGS. An additional purpose was the comparison of baseline results with those obtained by other techniques and from other GPS campaigns as a means of assessing the accuracy.

2. ANALYSIS SOFTWARE

All software used in the analysis of the SWP-90 data has been developed at the Center for Space Research (CSR) and is known collectively as TEXGAP (TEXas Gps Analysis Programs). The analysis process is divided into a preprocessing component and a geodetic component. In the preprocessing component, the data were reviewed and corrected for cycle slips, erroneous points and general data anomalies. In this process, the time tags of the phase measurements were validated and/or corrected using the L_1 C/A pseudo-range, or L_1/L_2 if the receiver operates with the P-code. Finally, explicit double difference ionospherically-corrected measurements were formed for the geodetic processing stage.

The geodetic processing was performed using MSODP1(Multi-Satellite Orbit Determination Program). In the general application of MSODP1, the GPS epoch orbit elements and selected force model parameters were simultaneously estimated with three-dimensional coordinates of the GPS. This software has undergone comparison with programs used for precision orbit determination of geodetic satellites, such as Lageos, Starlette and Etalon, all of which are targets for precision satellite laser ranging instrumentation [Tapley et al., 1985].

3. DATA AND MODELS

As previously noted, the GIG-91 data were used for the study as shown in Table 1. Although the network is dominated by Rogue receivers, TI-4100 receivers at W. Samoa and Easter Island were included to improve the southern hemisphere and Pacific coverage. In addition, a Minimac 2816 at Hobart was included because of the availability of a survey tie to VLBI at the time the investigation began; however, the local surveys have recently become available for Yaragadee and Tidbinbilla/Canberra.

The GPS force models followed the current IERS Standards [McCarthy, 1989] and scale factors on the ROCK4 [Fliegel, 1992] and y-bias parameters were estimated. The Chao [1973] troposphere model was used, and zenith delay parameters were estimated at 2.5 hour intervals from all sites. Lageos-derived polar motion and UT1 were used as a priori. For all cases, dual frequency double differenced phase measurements were used in the analysis. Pseudo-range measurements were used to verify and/or correct the respective receiver clocks.

The reference frame was based on Lageos satellite laser ranging (SLR) analysis, CSR91L03 [Eanes et al., 1991] and Very Long Baseline Interferometry (VLBI) analysis GLB718 [Ma et al., 1991]. The VLBI sites were transformed into the SLR reference frame using transformation parameters derived from 18 common sites. The technique has been described by Ray et al.[1991].

4. ESTIMATION STRATEGIES

For this study, two primary estimation strategies have been used and a third strategy was partially examined. The first strategy was based on independent one-day arcs in which orbit parameters (including y-bias and solar radiation pressure parameters), Earth rotation parameters (x,y) and station coordinates were estimated without a priori constraints (i.e., the a priori covariance was essentially infinite). The second strategy was based on a multi-day estimation of station coordinates,

but daily determinations of orbit, force model and Earth rotation parameters. For some cases that used this strategy, a priori covariance constraints were used. The third strategy was based on a multi-day orbital arc, but daily solutions for station coordinates and Earth rotation parameters were obtained.

It is well-known that the models used to describe the dynamics of the GPS satellites are incomplete or contain errors (or both). These model deficiencies will lead to a discontinuity at the common time point between successive one-day arcs and will produce higher RMS measurement residuals on multi-day arcs unless the model deficiency is accommodated by estimated parameters. The latter accommodation of errors may not produce improved model parameters as the unmodeled effect may have a signature similar to the other effects, thus allowing the model error to be absorbed in other parameters.

In the multi-day station coordinate strategy, all stations were allowed to adjust, also referred to as a "free fiducial" case by Blewitt et al.[1992] and others. This strategy leads to a very ill-conditioned, or nearly singular, problem when Earth rotation parameters are estimated also and requires the introduction of some a priori constraints. The constraint commonly used is an a priori covariance with coordinate uncertainties chosen to be a specified value, e.g., 100 meters. Other ways of avoiding the singularity are to fix the coordinates of some stations or a combination of coordinates at more than one station. The minimal number of constraints required depends on the parameters being estimated.

5. EARTH ROTATION RESULTS

Using the first strategy of independent one-day arcs and fixing the coordinates of Hobart, Goldstone and Wettzell to the values given in Table 2, the GPS orbit parameters, other station coordinates and (x,y) Earth rotation were estimated. Although all of the fixed sites were at VLBI locations, Hobart is a Minimac receiver and the other two sites use Rogue receivers. In any case, the RMS differences of the estimated rotation pole position, compared to Lageos values [Eanes et al., 1991] produced RMS differences of 1.5 mas in x and 1.4 mas in y after removal of a 5 mas bias.

In an alternative case, Yaragadee, Goldstone and Wettzell were fixed and all non-Rogue sites were eliminated. The RMS differences in pole position were 2.6 mas in x and 3.3 mas in y. Further investigation is required to determine whether the cause of the change is associated with the fixed coordinates of Yaragadee or with the exclusion of the non-Rogue receivers.

Using the strategy in which a multi-day solution was obtained for the stations in a "free fiducial" mode with 100 m a priori on the station coordinate covariance elements, 1 day solutions for pole position (x,y) were obtained using 10 mas a priori. The RMS differences of the pole position, compared to Lageos, were 0.8 mas in x and 1.0 mas in y. In all comparisons, the RMS differences will change slightly if the GPS results are compared against other Earth rotation series.

6. BASELINES

From the three fixed site strategy, the daily repeatability for baseline length on selected baselines is shown in Table 3. The selected cases are all cases in which double differences were directly

formed for the solution process. It can be noted that the repeatability for all cases involving the TI-4100 receivers exhibit worse repeatability than the other cases. It should be noted that for both W. Samoa and Easter I. the preprocessing identified some significant systematic features that could be related to multi-path problems.

An additional case was examined in which Trimble receivers at Wellington, New Zealand, and Townsville, Australia were included for the purpose of estimating the coordinates of these sites. In the case of Wellington, a result obtained during a 1990 campaign afforded an additional comparison. Data collected during July 1990 and processed as part of the Southwest Pacific Project (SWP) provided a set of coordinates for Wellington. The SWP results [Schutz et al., 1992] used a global network that differed from the GIG-91 in two primary ways. First, the SWP global network was dominated by "codeless" receivers and, second, Selective Availability (SA) was activated. As noted previously, the GIG-91 global network was dominated by Rogue P-code receivers and SA was not implemented. The comparison of the Hobart to Wellington baseline is given in Table 4 and the coordinates of the Australia/New Zealand sites derived from GIG-91 are given in Table 5.

7. CONCLUSIONS

Based on the preliminary results given in this paper, it has been shown that Earth rotation components (x,y) were obtained that agree with other determinations at the 1 mas level (RMS). Two strategies were examined: a multi-day case and cases using independent one-day arcs. Baselines from the three fixed site case show repeatability at the several ppb level, except for cases using the TI receivers in the Pacific which are at the level of 10-20 ppb. Further examination of the influence of mixing Rogue and TI data will be conducted and other estimation strategies are under examination.

Results for Wellington that were obtained from two campaigns show agreement at the 10 ppb level. In one case, the campaign was dominated by global codeless receivers, whereas the GIG-91 was dominated by Rogue receivers. An additional difference was the fact that SA was activated during the earlier campaign, but not during GIG-91.

8. ACKNOWLEDGEMENTS

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TABLE 1. GIG-91 SITES

Rogue Receivers:

Yaragadee, Australia	Wettzell, Germany
Canberra, Australia	Madrid, Spain
Santiago, Chile	Matera, Italy
Hartesbeestoek, S. Africa	Kootwijk, Netherlands
Kokee Park, Hawaii,	Ny Alesund, Norway
Usuda, Japan	Tromso, Norway
Goldstone, CA	Algonquin, Ontario
Victoria, BC	Yellowknife, NWT
Fairbanks, Alaska	

Minimac 2816AT Receiver:
    Hobart, Tasmania, Australia

TI-4100 Receivers:
    W. Samoa
    Easter Island

TABLE 2. COORDINATES USED FOR FIXED SITES (m)

Site	x	y	z
Goldstone (Rogue	-2353613.9840	-4641385.4730	3676976.4990
Hobart (Minimac L1)	-3950184.0724	2522364.5271	-4311588.6675
Wettzell (Rogue)	4075579.3868	931807.2475	4801570.9395

Note: The Rogue coordinates refer to the top of the antenna

TABLE 3. SELECTED BASELINES

Sites	Baseline Length (km)	Daily RMS Scatter (ppb of baseline length)
Algonquin - Wettzell	6154	5.6
Goldstone - Yellowknife	2986	8.8
Goldstone - Fairbanks	3807	6.3
Goldstone - Algonquin	3402	12.4
Yaragadee - Tidbinbilla	3197	8.9
Tidbinbilla - W. Samoa	4474	17.7
Kokee Park - W. Samoa	4124	22.2
Kokee Park - Usuda	5894	8.4

TABLE 4. COMPARISON OF HOBART-WELLINGTON BASELINE (m)

Case	x	y	z	L
SWP-90	-830464.717	-2085857.511	126148.175	2248641.049
GIG-91	-830464.699	-2085857.541	126148.187	2248641.070
Difference (xyz, L)	0.018	-0.030	0.012	0.021
Difference (NEU)	0.005	0.028	0.023	

(NEU: North, East, Up)

TABLE 5. COORDINATES OF SELECTED AUSTRALIA/ NEW ZEALAND SITES (m)

Data: GIG-91

| Site	x	y	z	
Hobart	-3950184.072	2522364.527	-4311588.668	Minimac L_1
Wellington	-4780648.771	436506.986	-4185440.481	Trimble L_3
RMS	0.051	0.017	0.032	
Tidbinbilla	-4460987.995	2682362.260	-3674626.550	Rogue L_3
RMS	0.025	0.013	0.033	
Townsville*	-5041024.956	3296980.304	-2090553.463	Trimble L_3
RMS	0.020	0.039	0.009	

RMS refers to the daily scatter in the solutions
* denotes that some solutions were edited

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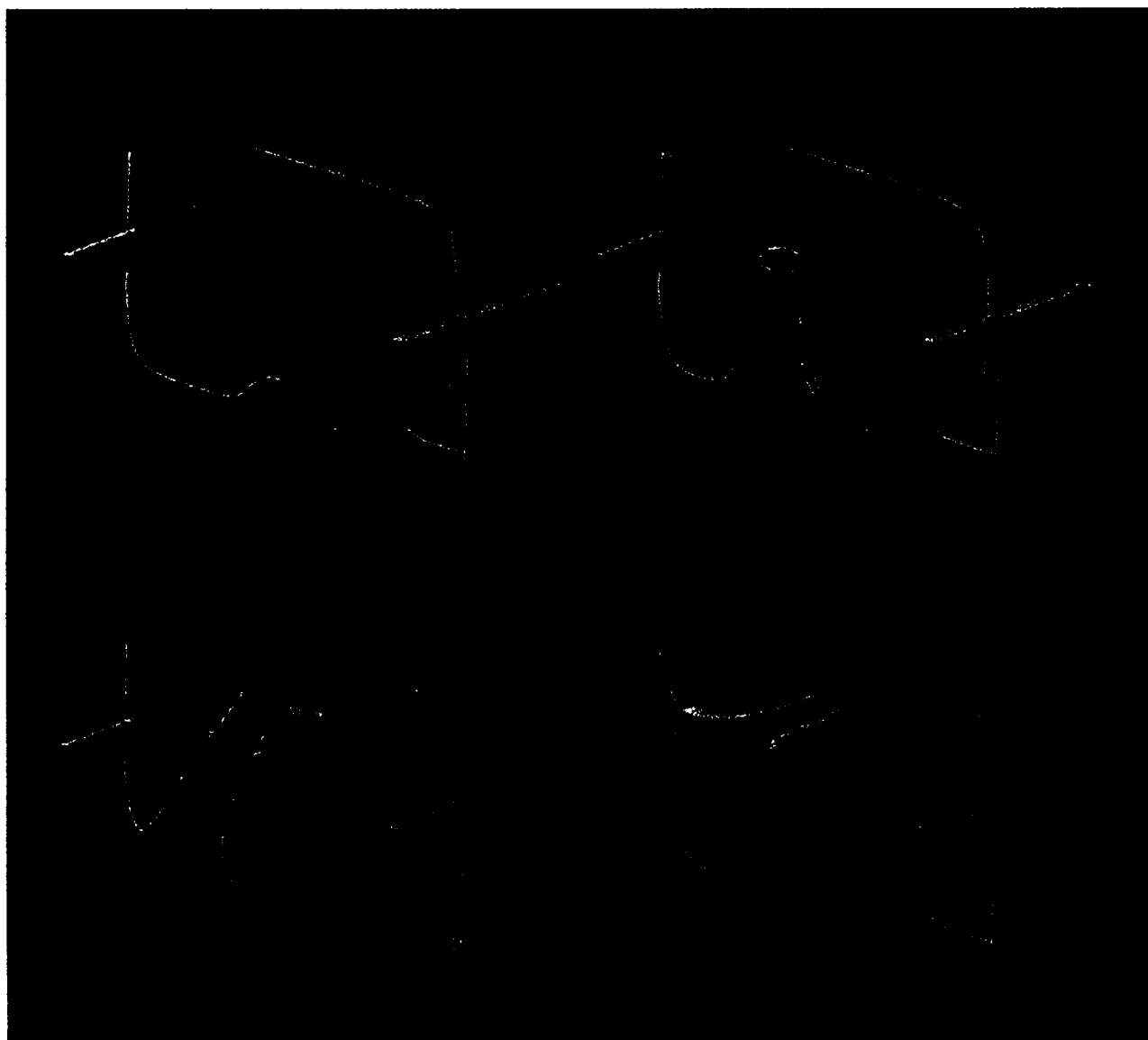
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GPS Reference Frames and Orbit Accuracy

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Analysis of GIG-91 data has been used to investigate nongravitational forces acting on the GPS satellites and their influence on the determination of geodetic parameters. It has been previously demonstrated that significant differences exist between the eclipsing and non-eclipsing satellites, which have prompted examination of eclipsing phenomena and associated forces. The analysis has been aided by the extended global tracking network available during the GIG campaign. The influence of the orbit accuracy on the reference frames is also examined, and comparisons between common sites with other campaigns will be made, using baseline lengths ranging from a few hundred kilometers to several thousand kilometers, with attention given to the determination of the vertical component.